Introduction to Industrial Gas Combustion Technology

A.N. Bogtstra
Preface

The purpose of this handbook is to provide users of combustion equipment with basic information on the most important types of burners for a wide range of applications. Such applications are classified as dryers, ovens, furnaces etc. Further, this handbook aims at providing the most important criteria for selecting combustion equipment for these applications.

It should be noted that this handbook has been compiled to serve as a manual, which in turn is the basis for general courses and instructions in industrial combustion. For this reason, its character is very general, purposely not specific.

This handbook is conceived so as to be useful for practical use. For this reason, we have chosen as a basis commercially available burner programs such as offered by a member of prominent manufacturers: Eclipse, Maxon, Stordy-Hauck, Selas of America, Schwank, Krieger, Urquhart, Rekumat. We have to emphasize here that this list of manufacturers is by far not conclusive. Other programs, such as offered by Bloom, North American, Pysonics etc., offer equipment with equal quality and applicability and not really other types of burners. Nevertheless, in order to keep this manual readable, we have felt obliged to make this selection.

We would like to thank the companies mentioned for making information and documentation available and for assisting us in putting this manual together in its present form.

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Note:
Zowel Energy Technologies want to make this useful knowledge available for a larger public, as the manuscript never made it to print. After scanning, we checked and edited it a little and made a table of contents with hyperlinks. I hope that works for the reader. Besides that, it is completely original. Comments are welcomed at secr@Zowel.com.

Jan Carpay, Company Director

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DEFINITIONS
- Gas burners
- Industrial Gas practise nomenclature

2 WAYS TO MIX GAS AND COMBUSTION AIR

a) The energy available in the gas pressure provides the mixing
   - Inspirator mixers
   - Some suggestions for applications and selection
   - High pressure inspirator for use with low pressure gas

b) The energy available in the air pressure provides mixing
   - aspirator mixers or low pressure proportional mixers

c) Combinations where gas and air pressure are used for mixing
   - multi ratio mixer
   - low pressure mixer
   - High pressure mixer

d) Suction device (fan) with proportioning valve takes care of mixing
   - Fan type mixer
   - Compressor mixers
   - Review of discussed mixers

3 BURNERS TO BE CONNECTED WITH MIXER SYSTEMS
- Flame stabilisation
- Prevention of flash back

1 Burners for open combustion
   - sticktite nozzles
   - spear flame sticktite nozzles
   - special burners for spot heating
   - Line burners to be fed with a stoichiometric gas/air mixture
   - Radiant burners
   - Radiant heat transfer (general)
   - Radiant heat transfer in more detail
   - Equipment and types of radiant burners
   - Ceramic impingement burner
   - Ceramic tile or grid type radiant burner
   - Some industrial applications
Matrix type with ceramic fibres and applications
Some other makes of industrial grid type IR-burners
Radiant tube type burner
Catalytic type radiant burner
Premix cup shaped radiant burner for oven and furnace applications

2 Burners for closed combustion tunnel or sealed in-nozzle burners

4 COMBUSTION FANS AND CONTROL VALVES
- Combustion fans
- Control valves and micro ratio valves
- Proportionater diaphragm valves

5 NOZZLE MIXING BURNERS

A Burners for ovens and furnaces
- Large capacity burners
- Flat flame burners
- High and medium velocity burners
- Radiant tube burners
- Luminous flame burners

B Burners for air heating applications
- Line burners without combustion air supply
- Line burners with partial combustion air supply
- Line burners with complete combustion air supply
- Line burners with stoichiometric combustion air supply
- Forward flame burners for air heating
- Line burners for incinerators
- Special Burner arrangement for air heating

6 BURNER RELATED SUBJECTS
- Calculations in air heating when applying gas for direct heating
- Burner piping
- Ceramic fibres for thermal insulation of gas fired furnaces
- Burner safeguarding
- Gas trains
7 BURNERS DESIGNED FOR CERTAIN APPLICATIONS
   - Immersion tube heating
   - Fume incineration
   - Supplementary firing in turbine exhaust heating

8 SPECIAL BURNERS
   - Recuperative and regenerative burners
   - Reduced and low NO\textsubscript{x} burners for air heating
   - Pulse combustion

9 APPLICATIONS
   - Dryers
     - Flash dryers
     - Spray dryers
     - Fluid bed dryers
     - Continuous tunnel and conveyor dryers
   - Furnaces and ovens
     - Reheat furnaces
     - Annealing furnaces
     - Aluminium melting
     - Hot dip galvanising (batch process)
     - Continuous hot dip galvanising (sendzimir process)
     - Annealing furnace and pickling line for stainless steel strip
     - Bright anneal line for stainless steel
     - Pottery production

REFERENCES

DESCRIBED AND MENTIONED APPLICATIONS
1 DEFINITIONS

Gas burners

Industrial burners may be classified as:

a) premix burners;
b) nozzle mixing burners.

Premix burners. In premix gas systems the primary air and gas are mixed at some point upstream from the burner ports by an inspirator mixer, an aspirator mixer or a mechanical mixer. The burner proper ("nozzle") serves only as a flame holder, maintaining the flame in the desired location. Theoretically, if mixture velocity equals flame velocity, a flame will stand stationary at any point at which ignition is applied. Actually however, a relatively cool burner nozzle (or port) is needed to serve as a flame stabilizer. If the flame advances too far into the port as a result of a momentary reduction in mixture velocity, the cool nozzle tends to quench it, in addition to accelerating the mixture velocity to prevent flashback.

The premix gas system will be discussed in chapter 2. The burners or nozzles will be discussed in chapter 3.

Nozzle mixing burners. As the name implies, the gas and combustion air do not mix until they leave the ports of this type of burner. The two fluids are kept separate within the burner itself, but the nozzle orifices are designed to provide mixing of the fluids as they leave.

There is a great variety of nozzle mixing burners on the market. In chapter 5 these burners are grouped in two types:

a) nozzle mixing burners for high temperature applications;
b) nozzle mixing burners (mainly line burners) for air heating.

Industrial Gas Practice Nomenclature

GLOSSARY

burner
premix burner
nozzle mixing burner
Turndown
Stability
Flame shape
Combustion volume
Drive

GAS / AIR SYSTEMS

Low pressure gas or "atmospheric" system
High pressure gas system
Low pressure air system
High pressure air system
Suction system
Two valve or micro ratio valve system
Mechanical system
MIXERS AND MIXING DEVICES

Mixer
Manual mixer
Automatic mixer
Gas jet mixer
Air jet mixer
Mechanical mixer

BURNERS
Burner, general.
Atmospheric burner
Blast burner
Pressure burner
Single port burner
Multiport burner
Line burner
Pipe burner
Ribbon burner
Open port burner
Tunnel burner
Flame retaining nozzle
Blast tip
Nozzle mixing burner
Proportional mixing burner
Radiant burner
Luminous flame burner
Ring burner
Multijet burner
Enclosed combustion burner
Diaphragm burner
Dual fuel burner, Gas/oil burner

Burner

A device for the final release of air/gas or oxygen/gas mixtures or air and gas separately into the combustion zone.

Industrial gas burners may be classed as atmospheric burners and blast or pressure burners. The functions of a burner are to deliver fuel and air to the combustion space (thus positioning the flame), to mix the fuel and air, to provide for continuous ignition of the fuel/air mixture and (in the case of liquid fuels) to atomise and vaporize the fuel.

Turndown. The range of input rates within which a burner will operate is specified by the burner turndown ratio. This is the ratio of the maximum to minimum heat input rates with which the burner will operate satisfactorily. For any burner with fixed air orifices, the turndown ratio is also the square root of the ratio of maximum to minimum pressure drops across the orifice. For example if the maximum supply pressure is 22 mbar and the minimum is 0,6 mbar, then the turndown ratio is $\sqrt{22/0,6} = 6$ to 1

The maximum input rate is limited by a phenomenon known as flame blow-off (which results from mixture velocity exceeding the flame velocity) and by the cost of equipment for developing higher pressures. The minimum input rate is limited by the phenomenon known as flash-back (which results from the flame velocity...
exceeding the mixture velocity) and by the minimum flow with which the ratio control equipment will function. The former limitation applies to premixing, but not nozzle mixing burners.

A high turndown ratio is particularly desirable in batch-type furnaces where a high input rate is needed during the initial heat-up of the furnace or immediately after charging, but where this high input rate cannot be used during the entire heating cycle. Considerably less turndown is needed for continuous furnaces which are seldom started from cold. The cost of an occasional long starting period may be less than the cost of the larger equipment required for a high turndown ratio. In some instances where temperature distribution is not too critical, it is possible to shut off some burners when on low fire and thus simulate a high turndown ratio.

Stability is another important characteristic of burners. A stable burner is one which will maintain ignition when cold and at the pressures and ratios ordinarily used (no burner is considered stable merely because it is equipped with a pilot).

Flame shape. For a given burner, operating variables such as changes in the mixture pressure or the amount of primary air will affect the flame shape. For most burner types an increase in mixture pressure will broaden the flame and in increase in the percent primary air will shorten the flame (input rate remaining the same). Flame thickness is reduced by higher ambient pressure and higher burning velocity. Burner design, which determines the relative velocities of the fuel and air streams has much more effect upon flame length and shape than either of the above operating variables.

Good mixing, produced by a high degree of turbulence and high velocities, produces a short bushy flame whereas poor mixing (delayed mixing) and low velocities result in long, lazy slender flames. Turbulence and good mixing may be promoted by the use of vanes in the streams to impart swirl. High pressure may tend to throw the fuel farther away from the burner nozzle before it can be heated to its ignition temperature and thus lengthen the flame. Figure 1 illustrates eight common flame types. Types 6 and 7 emit more flame radiation than the others, even when burning gas. Type 5 uses flame convection to heat adjacent refractory; so it heats a furnace load primarily by refractory radiation and is termed a radiant burner, radiation burner or an infrared burner.
Combustion volume. The space occupied by the fuel and the intermediate products of combustion while burning (flame and invisible combustion) varies considerably with the burner design, the pressures and velocities of the fluid streams, the fuel and the application. Gas burners with considerable refractory surface and operating with very high mixture pressure and thorough mixing may release as much as 1200 GJ/m³/h of combustion volume. The initial and operating costs are less where less compact combustion is required. The combustion volumes of other types of gas burners range all the way from the above-mentioned figure down to 3700 MJ/m³/h.

In some cases the application itself may limit the rate of heat release. In applications where long luminous flames are required, the delayed mixing type of burner probably will not release more then 1500 MJ/m³/h.

Drive. This Property of burners relates to the velocity and thrust of the jet stream of hot gases that they throw into a furnace. Type 8 of figure I is a burner designed to produce high drive.

When fuel was cheap, excess air was used to aid temperature uniformity within a furnace load by (1) reducing the hot mix temperature, (2) preventing stratification and (3) enhancing convection heat transfer. With high velocity burners that induce recirculation of furnace gases, the recirculating gases produce the above three benefits that formerly required excess air and therefore wasted fuel. The high velocity burners can push their hot gases into a loosely-piled load (such as castings...
or a hack of bricks) with greater velocities than were possible with most of the older excess air burners; so forced convection is improved to the interior of the load. Words such as pierce, punch, scrub and stir provide good mental images of the advantageous convection and agitation from, burners with "drive".

Another use for burners with drive is to reach and wrap around parts of a load located at a distance from the burners. This reduces the heating time for loads in furnaces with long dimensions parallel to the burner centre lines and for large pieces, the back side of which cannot be "seen", well by radiation or "reached" well by other types of convection burners.

A Gas/air proportioning and mixing systems for combustion

1. **Low pressure gas or "atmospheric" system** (gas pressure less than 70 mbar). A system using the momentum of a jet of low pressure gas to entrain from the atmosphere a portion of the air required for combustion.

2. **High pressure gas system** (gas pressure 70 mbar of higher). A system using the momentum of a jet of high pressure gas to entrain from the atmosphere all, or nearly all, of the air required for combustion.

3. **Low pressure air system** (air pressure 350 mbar). A system using the momentum of a jet of low pressure air to entrain gas to produce a combustible mixture.

4. **High pressure air system** (air pressure 350 mbar or higher). A system using the momentum of a jet of high pressure air to entrain gas, or air and gas, to produce a combustible mixture.

5. **Suction system**. A system applying suction to a combustion chamber to draw in the air and/or gas necessary to produce the desired combustible mixture.

6. **Two valve or micro ratio valve system**. A system using separate control of air and gas both of which are under pressure. The valves, controlling the air and gas flows, may or may not be interlocked.

7. **Mechanical system**. A system which proportions air and gas mechanically compresses the mixture for combustion purposes. A central mixing unit may be used for individual appliances may each have its own mixer.

B Mixers and mixing devices

1. **Mixer, general**. A device for mixing gas and air in any desired proportions.

2. **Manual mixer**. A mixer that requires manual adjustments to maintain the desired air/gas ratio as rates of flow are changed.

3. **Automatic mixer**. A mixer that automatically maintains within its rated capacity a substantially constant air/gas ratio at varying rates of flow. All types defined below can be designed to fit this classification.

4. **Gas jet mixer**. A mixer using the kinetic energy of a jet of gas issuing from an orifice to entrain all or part of the air required for combustion.
Commonly used names of gas jet mixers include: "injector", "lojector", "venturi mixer", "two stage mixer", "inspirator", "hijector", "tube mixer", "atmospheric mixer" and "bunsen mixer".

Air jet mixer. A mixer using the kinetic energy of a stream of air issuing from an orifice to entrain the gas required for combustion. In some cases this type of mixer may be designed to entrain some of the air for combustion as well as the gas. Commonly used names of air jet mixers include: "low pressure inspirators", "aspirators", "flomixers", "mixjectors", "mixing tees", "low pressure proportional mixers", "vari flame".

Mechanical mixer. A mixer using mechanical means to mix gas and air, neglecting entirely any kinetic energy in the gas and air and compress the resultant mixture to a pressure suitable for delivery to its point of use. Mixers in this group utilize either a centrifugal fan of some other type of mechanical compressor with a proportioning device on its intake through which gas and air are drawn by the fan or compressor suction. The proportioning device may be automatic or require manual adjustment to maintain the desired air/gas ratio as rates of flow are changed. Names of mechanical mixers include: "fan mix", "industrial carburetor", "premix", "fan type mixer", "combustion controller and diluter"

C Burners

1 Burner, general.

2 Atmospheric burner. A burner used in the low pressure gas or "atmospheric" system which required secondary air for complete combustion.

3 Blast burner. A burner delivering a combustible mixture under pressure, normally above 0.7 mbar to the combustion zone.

4 Pressure burner. Same as blast burner.

5 Single port burner. A burner having only one discharge opening or port.

6 Multiport burner. A burner having two or more separate discharge openings or ports. These ports may be either flush or raised.

7 Line burner. A burner whose flame is a continuous "line", from one end to the other. Normally applied to a blast burner.

8 Pipe burner. General term covering any type of atmospheric or blast burner made in the form of a tube or pipe with ports or tips spaced over its length.

9 Ribbon burner. A burner having many small closely spaced ports usually made up by pressing corrugated metal ribbons in a slot or other shaped opening.

10 Open port burner. Any type of burner that fires across a gap into an opening in the furnace or combustion chamber wall and is not sealed into
the wall. Burners of this type include: "torch burners", "tile burners", "box burners", "ventite burners", "burnix burners".

11 **Tunnel burner.** A burner sealed in the furnace wall in which combustion takes place mostly in a refractory tunnel or tuyere which is really part of the burner. Common names for tunnel burners include: "wall-tite burners", "impact burners", "hyperblo burners", "pyronic burners", "refrak", "tunnel".

12 **Flame retaining nozzle.** Any burner nozzle with built-in features to hold the flame at high mixture pressures. Names of flame retaining nozzles include: "sticktites", "ferrofix", "staylites", "F.R. nozzles".

13 **Blast tip.** A small metallic or ceramic burner nozzle so made that flames will not blow away from it, even with high mixture pressures.

14 **Nozzle mixing burner.** A burner in which the gas and air are kept separate until discharged from the burner into the combustion chamber or tunnel. Generally used with low pressure gas (up to 35 mbar) and low pressure air (up to 350 mbar).

15 **Proportional mixing burner.** An assembly which incorporates an automatic mixer and a burner as an integral unit. Trade names include: "L.P. velocity", "H.P. velocity", "walltite".

16 **Radiant burner.** A burner designed to transfer a significant part of the combustion heat in the form of radiation from surfaces of various shapes which are usually of refractory material. Trade names include: "red ray", "duradiant", "burdette".

17 **Luminous flame burner.** A burner which discharges non-turbulent parallel strata of air and gas to produce an extended flame of high luminosity.

18 **Ring burner.** There are two types:
   a) a form of atmospheric burner made with one or more concentric rings;
   b) a form of burner used in firing boilers consisting of a perforated vertical gas ring with air admitted generally through the centre of the ring. Combustion air may be supplied by natural, induced or forced draft.

19 **Multijet burner.** A form of burner which generally consists of gas manifolds with a large number of jets arranged to fire horizontally through openings in a vertical refractory plate. These openings are of various shapes - round, square, clover-leafed etc. Combustion air may be supplied by natural, induced or forced draft. Complete assemblies combining burner, refractory plate, wind box, blower and controls are generally known as forced draft boiler burners. Trade names include: "lo-blast", "fanmix", "flame king", "gas pak".

20 **Enclosed combustion burner.** A burner which confines the combustion in a small chamber of miniature furnace and only the high temperature completely combusted gases, in the form of high velocity jets or streams, are used for heating. Trade names include: "super-heat", "zigzag".
21 **Diaphragm burner.** A burner which utilizes a porous refractory diaphragm as the port so that the combustion takes place over the entire area of this refractory diaphragm.

22 Dual fuel burner. A burner designed to burn either gas or oil, but not both together.

23 Gas/oil burner. A burner designed to burn gas and oil simultaneously.

24 Combination gas and oil burner. A burner which can burn either gas or oil or both together.
2. WAYS TO MIX GAS AND COMBUSTION AIR

There are 5 ways to mix gas fully or partly with combustion air:

a) the energy available to the gas pressure provides the mixing;
b) the energy available in the air pressure provides the mixing
c) combinations where gas and air pressures are used for the mixing
d) a suction device such as a fan with mixer provides the mixing
e) gas and combustion air are mixed just after the nozzle (nozzle mix burner); will be discussed in chapter III.

If stated that the gas pressure will take care of the mixing it means that the kinetic energy available from the gas pressure gives a high gas velocity from the gas nozzle is used for injecting and mixing combustion air.
In the same way high combustion air pressure will be able to inject gas.

a) THE ENERGY AVAILABLE IN THE GAS PRESSURE PROVIDES THE MIXING

Inspirator mixers

Atmospheric mixers
High pressure inspirator

Some suggestions for applications
High pressure inspirator for use with low pressure gas

Inspirator mixers

As stated, the gas pressure is utilized to inject the air. Or in other words, the energy in the gas is utilized to induce primary air in proportion to the gas flow. The air required for combustion is injected by the high velocity gas jet. No blower or fan is required. The amount of air that is drawn in varies in proportion to the pressure of the gas at the spud. Thus the ratio of fuel to air is maintained throughout the normal operating range.
In industry these mixers are classified in two types:
- Atmospheric low gas pressure mixers
- High pressure inspirator mixers

Atmospheric mixers

Atmospheric mixers are those mixers which operate under gas pressures of 5 to 25 mbar of water pressure, utilizing that pressure to induce or inspirate a portion of the air necessary for combustion. An example of this type of gas burner system is the one commonly used in domestic gas applications where the gas from the main (under pressure varying from 5 to 25 mbar) passes through a jet (called a spud) in the inspirator or mixer head. Its velocity and mass (kinetic energy) induces atmospheric air to be drawn through the air register in the mixer head and mixed with the gas. The mixture then proceeds to the burner tip or nozzle where it is ignited.

The amount of atmospheric air which is drawn in with the gas usually amounts to 40 to 60% of the total air necessary for complete combustion of the gas. The balance of the
air, lust, of course, come from some other source such as the atmosphere surrounding the flame at the burner nozzle.

In installing or operating atmospheric gas burners, this important characteristic must not be overlooked. Means must be provided to assure additional air supply for the flame, as the mixture of air and gas coming out of the burner port or nozzle is not sufficiently aerated to permit proper combustion.

Atmospheric gas burners are an important type of heat generating equipment, as they are used in the field of low temperature heating processes, such as small boilers, compound kettles, glue melting, baking, air preheating etc. The design of burner inspirators and nozzles is completely standardized.

Figure 2 shows a variety of some open atmospheric burners

![Figure 2: Atmospheric burners (Eclipse)](image)

**High pressure inspirator mixing systems**

High pressure inspirator mixing systems are those which operate with gas pressures from 0.07 bar upward depending on the heating value of the gas. They are similar to atmospheric inspirators wherein it is desirable to produce the correct proportional mixing of air and gas for complete combustion. An adjustable air shutter is provided on the mixer so that the proper air and gas ratio can be secured and, once set, maintain the proper ratio of air and gas over the normal capacity of the mixer. In this type of mixer, the kinetic energy of the gas must be sufficient to draw in through the mixer air shutter, 100% of the necessary air for combustion.

The pressure of the gas to perform this is approximately in proportion to the thermal quality of the gas. For example, a high pressure burner utilising gas of 11 MJ/m³ will require approximately 0.35 bar of gas pressure. A gas of 20 MJ/m³ heating value should have approximately 0.7 bar for proper burner operation. Similarly, 37 MJ/m³ gas should have about 1.5 bar gas pressure for proper burner operation.

Control of these mixers, either by hand or automatic, is secured by a valve in the gas line to the mixer, since the air induced by the gas varies in proportion to the gas flowing over the range of the mixer. {15}
These mixers can be combined with a variety of single or multiple nozzles, drilled pipe type, ribbon type, torch type, or any one of the many shapes and designs that are available and that may be suited to a particular operation. The area ratio of the burner nozzle to the inspirator spud and inspirator throat is highly important and any given high pressure inspirator will work properly only when these ratios are correctly chosen.

Figure 3: High pressure gas/air inspirator (Stordy-Hauck)

In most industrial burner catalogs information is given which type of nozzle or nozzles should be applied on a certain inspirator with a certain spud. To figure the burner nozzle size to the inspirator spud area, the table in figure 4 should be used.

<table>
<thead>
<tr>
<th>Gross heating value of the gas (MJ/m³)</th>
<th>Burner area nozzle to spud area ratio Combustion chamber Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>negative</td>
</tr>
<tr>
<td>19.75</td>
<td>40..60</td>
</tr>
<tr>
<td>29.8</td>
<td>60..80</td>
</tr>
<tr>
<td>37.25</td>
<td>80..100</td>
</tr>
<tr>
<td>55.8</td>
<td>120..140</td>
</tr>
<tr>
<td>93</td>
<td>150..170</td>
</tr>
<tr>
<td>119</td>
<td>250..270</td>
</tr>
</tbody>
</table>

The given figures in above table are used to multiply the jet or spud area by to determine the proper burner nozzle opening area.

Figure 5 gives a chart for finding the "high pressure inspirator manifold pressures". These pressures will normally be developed by these inspirators at various fuel gas pressures, with the different caloric gases when used with spud to burner area ratios as listed in table of figure 4. [16]
Figure 5: Normal manifold pressures developed by high pressure inspirators

For selecting the size of burner nozzle openings for high pressure inspirators the chart in figure 6 can be consulted which indicates the allowable MJ-capacity per square cm of burner opening for various manifold pressures.\cite{17}
"Burner nozzle discharge coefficients" which give the percentage of the full discharge area that the nozzles will pass are given in figure 7.

It will be noted that one square cm of burner nozzle area will pass varying amounts of mixture depending upon the shape of the nozzle. These discharge coefficients should be taken into consideration when usual nozzle designs are to be supplied with an air/gas mixture from a high pressure inspirator. For example, when figuring the jet to nozzle ratio of a high pressure inspirator for a gas burner nozzle made from a pipe cap with a number of small drilled openings, the burner opening area should be taken as 60% of the full area of all the openings and then, from this new area, the jet size can be figured.

Some suggestions for applications

Constant gas pressure should be supplied to these inspirators to eliminate the necessity of readjusting the gas valve to compensate for the fluctuating pressure.
To obtain a minimum loss in mixture pressure, only as few elbows as possible should be used in the mixture piping from the outlet of the mixer. Where multiple burners are to be fed by one inspirator, the mixture piping should be large enough and usually one pipe size larger than the mixer outlet to avoid undesirable pressure loss.

The inspirators are supplied with a spud having the correct size jet opening which will deliver the required gas volume within the range of the mixer size.

Gas capacities of inspirators and burners are affected by the pressure existing in the combustion chamber. The gas capacity of an inspirator is normally based upon a zero pressure in the combustion chamber. When the combustion chamber operates under pressure up to 0.6 mbar, the gas capacity of the inspirator may have to be reduced 50%. When the combustion chamber operates under a draft down to 0.6 mbar, the capacities can be increased up to 50%. In that case spud has to be taken accordingly larger.

For capacities of gas spuds, the American tables from figures 8 and 9 can be consulted which give the areas and capacities of gas spuds under various pressures and specific gravities.

Figure 8,9: tables: CAPACITIES OF ORIFICES FOR HIGH PRESSURE GAS

Figure 10: Inspirator (Eclipse) with Sealed in nozzle. The inspirator includes an adjustable primary air shutter. The secondary air inlet can be adjusted by adjustable openings.

Figure 11: Inspirator with nozzle for immersion heating of Solutions. Burner fires into immersed pipe coil or tube (Eclipse). Applications include: Water heating, Parts cleaning, Bottle washing, Potato chip cooking, Low temperature metal melting
Figure 12: Salt or acid baths, Quenching or tempering tanks, Plating solutions, Salt descaling, Asphalt heating

As stated most industrial burner catalogues are giving complete information on inspirators with nozzle or burner combinations. Next are some catalogue examples.

Maxon catalogue

Combination inspirator with sticktite nozzle as shown in figure 13.

![Figure 13: Inspirator with sticktite nozzle (Maxon)](image)

Figure 13: Inspirator with sticktite nozzle (Maxon)

Figure 14: Capacity table for inspirators (Maxon, Capacities in CFH of Gas Against Balanced Pressures)

Inspirators are designated as to size in accordance with the standard pipe size of the air/gas mixtures outlet of the mixing tube. Capacities of inspirators shown in above selection table are based upon the use of the following single sticktite nozzles screwed directly on the threaded outlet of the inspirator.

<table>
<thead>
<tr>
<th>Inspirator</th>
<th>1″</th>
<th>1 1/4″</th>
<th>1 1/2″</th>
<th>2″</th>
<th>2 1/2″</th>
<th>3″</th>
<th>4″</th>
<th>5″</th>
<th>6″</th>
<th>8″</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sticktite nozzle</td>
<td>1″-9</td>
<td>1 1/4″-14</td>
<td>1 1/2″-18</td>
<td>2″-14</td>
<td>2 1/2″-27</td>
<td>3″-30</td>
<td>4″-41</td>
<td>5″-50</td>
<td>6″-60</td>
<td>8″-80</td>
</tr>
</tbody>
</table>

Eclipse catalogue

Combination inspirator with sealed nozzle as shown in figure 15.
Selection:
Burner type: For a given burner output diagram from figure 16 determines the required burner type depending on type of gas and gas pressure. The diagram assumes a negative pressure in the combustion chamber of 2.5 mm w.c. When the negative pressure in the combustion chamber exceeds 2.5 mm w.c. the burner selected will have a larger output than required (see table figure 17) and the burner is to be adapted then accordingly.

Figure 16: Selection diagram

<table>
<thead>
<tr>
<th>combustion chambers pressures in mm WC</th>
<th>200</th>
<th>1000</th>
<th>&gt;1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>(negative) V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0,5-2,5</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>1,1</td>
<td>1,02</td>
<td>1</td>
</tr>
<tr>
<td>7,5</td>
<td>1,15</td>
<td>1,04</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>1,25</td>
<td>1,06</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>1,5</td>
<td>1,15</td>
<td>1</td>
</tr>
</tbody>
</table>
Gas orifices
The required bore of the orifice can be determined for the available type of gas, gas pressure and capacity from figure 19.
When sizing the orifice care should be taken not to exceed the maximum bore of the orifice (see figure 20).

Figure 17: Multiplier for burner outputs at various negative pressures

Figure 18: Relationship between capacity and flame length
Figure 19: Orifice size selection

Figure 20: Specifications (Eclipse)

Stordy-/Hauck catalogue (26)

The selection table is based on combinations of inspirator with Sticktite or sealed nozzles having the size of the mixer discharge.
High pressure inspirator for use with low pressure gas

Where higher temperatures and capacities are required than can be developed with low pressure gas only, the high pressure air/gas booster can be used when high pressure air is available. The gas pressures in some cases can be as low as 5 mbar at the inspirator, depending on the required and available volume of gas.

The booster unit can be used to supply gas mixtures to any type of burner nozzle or nozzles for furnace or oven firing. It is also very useful as a portable gas/air mixer with a burner nozzle for ladle drying, cupola lighting and other heating applications where occasional or infrequent operating periods could not warrant the purchase of a low pressure air blower and mixer.

As illustrated in figure 21 the booster has a hollow needle which directs the high pressure air flow through the centre of the gas spud and causes the gas to be drawn in around the jet of air. With this arrangement, only a small portion of the air for combustion needs to be high pressure, because the high pressure air inspirates a large portion of atmospheric air and at the same time mixes the gas and air. By admitting the high pressure air in this manner, the danger of forcing air back into the gas line is eliminated.

The one unit serves the double purpose of an air inspirator to reduce the high pressure air and to entrain atmospheric air, and as a mixing tee to mix the developed lower pressure volume air with the gas.

Desired blast and volume of flame is secured by adjusting the air and gas cocks which are supplied.
The capacities of the booster are dependent upon the air pressure and volume of gas available. [28]

Figure 22: High pressure inspirator (Eclipse)

Sometimes these high pressure inspirators are applied to supply air to a low pressure proportional mixer (this mixer will be described later). See figure 23. This system eliminates a combustion fan and might be particularly useful if infrequent service is expected (start-up procedures etc.).

Figure 23: High pressure inspirator or airjector to supply combustion air to a proportional mixer (Eclipse)

Proper method of selection is to use an airjector of the same outlet size as the inlet size of the mixer. Mixers should be purchased without an air valve since control is accomplished through use of a valve in the compressed air line.

b. THE ENERGY AVAILABLE IN THE AIR PRESSURE PROVIDES THE MIXING[29]

As stated, here the air pressure is utilised to inject the gas. For this type of mixer a blower is required to produce up to 200 mbar air pressure. The amount of gas that is drawn in varies in proportion to the air pressure at the spud. In industry these mixers are generally called low pressure proportional mixers or aspirator mixers.

Low pressure proportional mixer systems utilise low pressure air from a blower or fan (up to 210 mbar), to inspirate or draw in low pressure gas. The gas is maintained at some constant pressure, usually zero, by a regulator (see figure 24). The gas is automatically entrained and mixed with the air in the correct gas/air ratio over the entire range of operation.
The air pressure that should be provided by the combustion air blower will depend on the turndown range required and will vary according to the applications, but in general the air pressure needed for these mixers is about 3.5 to 4 times the mixture pressure. An adjustable valve between the zero regulator and the inspirator chamber is provided as a means of adjusting the air/gas ratio. Once this valve is properly set, the mixer maintains this ratio over the range of the mixer capacity. This valve also makes it possible to use this type of mixer with a wide variety of calorific gases.

This type of mixer can be used in many different types of applications. It is relatively cheap to operate, easily controlled and requires only a low pressure blower which may be installed close to the point of gas consumption. Excellent flexibility of capacity with accurate automatic air/gas proportioning is one of its principal advantages. Gas of any thermal value can be used in this mixer. However, the relationship between the burner nozzle discharge area, the inspirator throat and the air jet dimensions are highly important and must be kept within a specified range.

This system is controlled by a single air control valve, by hand or automatic instrument and thus gives a very accurate temperature and atmospheric control. This system eliminates the need to regulate both the gas and air valves as the heat requirements change. This mixer may also be used to supply practically any type or shape of burner nozzle which is required for a specific heating operation, but when applying these mixers to burners which have an intricate discharge port, the flow characteristics of this port, or its discharge coefficient should be taken into consideration in determining the proper mixer to supply such burners.

![Diagram of low pressure air/gas proportional mixer](image-url)
Figure 25: Low pressure proportional mixer (Eclipse)

Operation (see figure 25):

Here the operation of a mixer is described.

The complete mixer consists of a manual butterfly valve, a venturi tube and air jet combined to create a suction, an accurate cone-type valve for gas/air ratio adjustment, a zero gas governor, and a level handle gas shut-off cock.

The gas cock is provided to shut off the gas supply when the system is not in operation, as the zero governor is not a tight shut-off valve.

Referring to the sketch, as the air flows through the jet "B" into the venturi tube 'C", a suction is created in the suction tee "A". This suction will vary with the velocity of the air flow through the jet. The gas is entrained and mixed inside the venturi sleeve. Its flow into the tee is set by the ratio adjuster valve I'D" and will vary directly in proportion to the air flow. If the gas varies in calorific content or specific gravity, a simple change in the setting of the cone adjuster I'D" will again provide the correct mixture. To secure highly accurate gas/air ratio control, the gas pressure must be reduced either to atmospheric or to the same pressure or suction condition as exists in the combustion chamber. If the burners being used are firing in the open or into a furnace at zero pressure, the governor is used with with the breathing vent "E" open to the atmosphere. If a suction or pressure condition exists, a pipe or tubing should be run from "E" to the combustion chamber. The governor will then deliver gas only when air flows through the mixer. If only very low air pressure is available (18 mbar), the suction in the entrainment tee may act be sufficient to draw enough gas through the governor to maintain proper gas/air ratio. In this case, an impulse line with bleed fitting should be installed between the air manifold, downstream of control valve, and the top diaphragm chamber of zero governor. As a result, any change in air flow is transmitted to the zero governor, and gas/air ratio is maintained throughout the range of operations.

Another proportional mixer is shown in figure 26.
The shown mixer is easy to adjust on site for required results and eliminates changing of jets, venturi, sleeves etc. The inverted iris cone is expanded or reduced in diameter by means of the external capacity adjustment screw for setting the desired maximum flow rate. Exact mixture pressure is thereby quickly set for correction of various burner nozzle coefficients of discharge and manifold designs without changing parts.

Accurate proportioning of gas and air is secured by the use of a zero gas governor (as described with the other mixers). The amount of gas drawn through it, will automatically vary in direct proportion to the amount of air flow through the mixer. The mixture can be made richer or leaner by the ratio adjustment screw.

Another proportional mixer is shown in figure 27. This mixer combines an adjustable throat and an adjustable venturi.

The complete mixer consists of a manually controlled air butterfly valve, a venturi casting with integral, adjustable throat blades for air/gas ratio adjustment, a zero gas governor and a level handle gas shut-off cock.

Referring to above sketch, as air flows past the adjustable throat blades "A" and "B", through the adjustable jet "C" into the venturi tube "D", a suction is created in chambers
'IF' and 'IF', entraining gas that has been reduced to zero pressure by the zero gas governor, and mixing it with the air in the venturi. If the gas varies in calorific content or specific gravity, a simple change in the gas selector, "G., will again provide the correct mixture.

If these mixers are delivered for applications where nozzle port areas are not known, the important spud (gas spud) nozzle area ratio can be adjusted with these types of mixers.
Figure 28: Typical piping arrangements of proportional mixers serving multiple burners (Stordy-Hauck)

c) COMBINATIONS WHERE GAS AND AIR PRESSURES ARE USED FOR MIXING [34]

This chapter will discuss a number of mixer types to provide properly proportioned gas/air mixtures for combustion. Depending upon the available gas pressure a proper mixer should be selected, for a certain gas/air mixture pressure (max. about 25 mbar in practice). The mixer selection depends upon the available gas pressure.

At a high gas pressure only a rather low air pressure is needed to achieve the needed mixture pressure. At a low gas pressure a high air pressure is needed for a certain mixture pressure.

Since high pressure combustion air costs more than low pressure combustion air one should try to utilise the available gas pressure as much as possible.

The next graph (figure 29) gives the average energy consumption of combustion blowers.

In the next pages we will first discuss different makes of mixers for low pressure gas before we shall look into mixers for rather high gas pressures.

Figure 29: Energy consumption of combustion fans

Multi-ratio low pressure proportional mixers
The mixer here described utilises low pressure air from a blower fan (up to 80 mbar pressure) to inspire or draw in low pressure gas which is maintained at a constant pressure (8-35 mbar depending upon the quality of the gas) into the combustion air stream. To achieve the correct air/gas ratio over the entire range of operation these mixers are provided with a linked air and gas control valve system. Accurate proportioning of the air and gas is maintained by an adjustable cam-strip provided in the gas valve system to maintain a constant air to gas ratio over all firing rates (see figure 32). These so called micro ratio air/gas valve systems will be discussed later.

The selection of the interchangeable air orifice is important for the ratio to the nozzle discharge area. This can be seen in the table of figure 33 where e.g. a MR 200-70 can be selected with a HD 2"-21 nozzle. The number 70 is the diameter of the air orifice which is 70/64 inch and 21 means 21/16 inch.

The air pressure that should be provided from the combustion blower will depend on the turndown range required.

The combustion air Pressure needed for these mixers is about 2-2.5 times the mixture.

Figure 30: Multi-ratio mixer (Maxon)

This mixer may also be used to supply practically any type or shape of burner nozzle which is required for a specific heating operation.

Multi-ratio mixers are most widely used for large multiple-zone furnaces or ovens for batteries of small processing units which are operated simultaneously. In such applications the combustion air for several mixers is supplied from one centrally-located blower. Where a central blower system is available with ample capacity to handle the additional load, the multi-ratio mixer system is quite low in initial cost (see figure 30).
In production furnaces through which the work is pushed or conveyed continuously, wide variations in heat input are required along the length of the processing unit as the work is first brought up to temperature, then held at temperature and finally in some cases even dropped to a lower temperature. This requires dividing the furnace or oven into two or more zones in which heat input may be independently controlled.

Multi-Ratio mixers are ideally suited for application to such units. A separate mixer is used on each zone of control with combustion air for all zones delivered from one centrally-located blower.

Figure 32: Inside a multi-ratio mixer (Maxon)

Figure 33 shows how a selection table of combinations multi-ratio mixers with one or more sticktite nozzles.
Figure 33: Selection table for multi-ratio mixer with sticktite nozzles (Maxon)

Figure 34 shows a same type selection table for combinations of multi-ratio mixers with sealed nozzles.

Figure 34: Selection table for multi-ratio mixer with sealed nozzles (Maxon)
Low pressure mixer
This mixer is of similar construction and working principle as the described multi-ratio low pressure proportional mixer, only without air and gas proportioning control valve (see figure 35).
For this reason these mixers must be applied with micro-ratio air/gas proportioning valves to provide properly proportioned supply of air and gas.

Figure 35: Low pressure mixer (Maxon)

Operation
The combustion air flow through the throat of a low pressure mixing tube maintains a continuous suction on the gas inlet chamber, injecting and mixing the gas proportioned to the mixing tube by the micro-ratio valve. The gas shading disc permits individual balancing out of fuel-air ratio to compensate for variations in frictional loss in piping when multiple mixing tubes are used with a single micro-ratio valve.

The low pressure mixing tubes are used where the piping manifolds to multiple burner nozzles are unavoidable long or complicated. This assures maximum air/gas mixture pressure at the burner nozzles, since an individual mixing tube discharges directly into each nozzle or line burner inlet connection.

Air and gas for a group of low pressure mixing tubes are proportioned by a centrally-located micro-ratio valve, operated automatically if desired (see figure 36).

Figure 36: typical application of low pressure mixing tube (Maxon)
Figure 37 shows a selection table for combinations of low pressure mixers with sticktite nozzles. This selection table is almost similar to selection table shown in figure 33 for multi-ratio mixers with the difference that the required combustion air is about 4 mbar (40 mm WC) lower due to the fact that in the low pressure mixers no resistance from an air control valve is there.

From the table can be seen that about 61 mbar combustion air pressure is needed to produce about 27 mbar mixture pressure. (Square of turndown ration times minimum mixture pressure which is 0.65 mbar. This gives 6.52 x 0.65 = 27.5 mbar).

**High pressure mixer**

This mixer is designed to give a certain mixture pressure at rather low (low in comparison with any other Mixer) combustion air pressure and rather high gas pressure. In normal cases the gas pressure at the mixer must be 150 mbar or 70 mbar higher than the air pressure. The combustion air pressure should be 35 mbar to produce 20 to 25 mbar .3 times

This mixer should be selected when enough gas pressure is available, which is very often the case. Since the mixer is not of the venturi type, the “HG” mixer must be combined with a Micro Ratio air/gas proportioning valve to provide properly proportioned air/gas mixture for combustion.
Figure 38: High pressure mixer (Maxon)

Figure 39 lists capacities in kW that may be expected when firing on open-port, 100% primary air, into a chamber having a slight positive internal pressure. While the table includes ratings with a 70 mbar combustion air blower (61 mbar at the mixing tube), the mixture pressures resulting from this combination will be relatively high (43 mbar to 53 mbar) meaning that near stoichiometric air/gas mixture will be important to proper nozzle flame retention. Listed rating allows for a 9 mbar drop in the combustion air pressure from blower outlet to high pressure mixer tube air inlet; but near-zero drop is assumed in mixture pressure from tube to nozzle; therefore this run should be relatively short and free of elbows.

<table>
<thead>
<tr>
<th>SIZE</th>
<th>STICKTITE</th>
<th>kW</th>
<th>COMBUSTION AIR BLOWER PRESSURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>TUBE</td>
</tr>
<tr>
<td>2&quot;-HG</td>
<td>HD-2&quot;-24</td>
<td>46</td>
<td>239</td>
</tr>
<tr>
<td>3&quot;-HG</td>
<td>HD-3&quot;-30</td>
<td>71</td>
<td>342</td>
</tr>
<tr>
<td>4&quot;-HG</td>
<td>HD-4&quot;-41</td>
<td>132</td>
<td>633</td>
</tr>
<tr>
<td>6&quot;-HG</td>
<td>HD-6&quot;-60</td>
<td>293</td>
<td>1466</td>
</tr>
<tr>
<td>8&quot;-HG</td>
<td>HD-8&quot;-88</td>
<td>704</td>
<td>3222</td>
</tr>
</tbody>
</table>

Figure 39: Capacity table of high pressure mixers (Maxon)

d) A SUCTION DEVICE SUCH AS A FAN WITH A PROPORTIONING VALVE SYSTEM TAKES CARE OF THE MIXING

There are two types of suction devices:
-fan-type mixers;
-compressor and blower type mixers.

Fan-type mixer

This chapter will describe the fan-type mixers for accurately proportioning and mixing gas and air, delivering the mixture under pressure. Gas at a regulated pressure is admitted to an air-gas ratio valve system like the micro-ratio valve (multiple set screw adjustment), which is mounted on the inlet of the centrifugal fan. The combustion air is drawn in from atmosphere by the fan through the air damper on the inlet of the fan. Gas and air are proportioned by the ration valves and mixed in the blower. The mixture is delivered under pressure to the burner manifold. The fan in fact combines the combustion blower and mixer.

Since there is no mixer pressure drop these systems in general are using less electrical (about 30% less) energy than any other mixer system. These devices can be connected with any clean gaseous fuel supplied at any uniform pressure between 5 and 20 mbar. It may be expected that these mixers are cheaper than other proportional mixing systems with separate combustion fan.

The European practice however showed that the from the States imported systems were more expensive than the mixer systems discussed in chapters IIb and IIc. The reason for this may be that the fan construction is more expensive than that of normal fans due to the fact that these fans must be constructed gas-tight and internally spark free. Many safety departments do not like the system due to the fact that a stoichiometric mixture flows inside the fan housing e

Figure 40: Mechanical type blower mixer
Figure 41: Fan mixer with control motor (Eclipse)

<table>
<thead>
<tr>
<th>MAX. CAP’Y MJ/hr</th>
<th>MIXTURE PRESSURE IN MBAR</th>
<th>MOTOR H.P.</th>
</tr>
</thead>
<tbody>
<tr>
<td>791</td>
<td>16</td>
<td>1/3</td>
</tr>
<tr>
<td>1055</td>
<td>24.6</td>
<td>1/3</td>
</tr>
<tr>
<td>1583</td>
<td>21.3</td>
<td>1/2</td>
</tr>
<tr>
<td>2110</td>
<td>18.3</td>
<td>1/2</td>
</tr>
<tr>
<td>2638</td>
<td>14.2</td>
<td>1/2</td>
</tr>
</tbody>
</table>

Figure 42: Capacity table of fan mixer 'Eclipse)
Compressor type Mixers

A special field of premixing devices are formed by motor driven compressors. These compressors deliver a proportioned mixture of air and gas under much higher pressures than discussed up till now. These high mixture pressures are applied where a high velocity hot jet on a precise area is needed (spot heating). Other applications are heating of very narrow bands on plates or surface hardening etc.

The smaller compressors of this type of premixing equipment are equipped with sliding block positive displacement compressors, the larger units have multi centrifugal blowers. These compressors are equipped complete with air filter and adjustable mixing valve. The delivered mixture pressure of these units is maximum 210 mbar for the small systems and maximum 280 mbar for the centrifugal type blowers. At these mixture pressures a turn down ratio of 25:1 is possible.

Review and summary of all previously described mixers
<table>
<thead>
<tr>
<th>Type of</th>
<th>Qualities</th>
<th>Gas enters</th>
<th>Air enters</th>
<th>Gas pressure</th>
<th>Air pressure</th>
<th>Mixture</th>
<th>Turbine</th>
<th>Micro-Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>boiler</td>
<td></td>
<td>X</td>
<td></td>
<td>19 bar at</td>
<td></td>
<td></td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>aspirator</td>
<td></td>
<td>X</td>
<td></td>
<td>20 to 300</td>
<td></td>
<td></td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Meule multitreated (combustion Micro-Netz)</td>
<td>X</td>
<td>3-6</td>
<td>36</td>
<td>33</td>
<td>3,4 : 1</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colpite proportional mixer: series (with continuously)</td>
<td>X</td>
<td>mixture press.</td>
<td>50 mbar min.</td>
<td>100</td>
<td>half of air pressure</td>
<td>9 : 1</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Colpite vertical mixer</td>
<td>X</td>
<td>zero gas generator</td>
<td>130</td>
<td>28-380</td>
<td>7 : 1</td>
<td>no</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meule 40 mixing tube</td>
<td>X</td>
<td>-</td>
<td>140</td>
<td>20</td>
<td>19-25</td>
<td>3,5 : 1</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Colpite and Meule for lean mix</td>
<td>X</td>
<td>-</td>
<td>5-20</td>
<td>10</td>
<td>6 : 1</td>
<td>yes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the previous pages mixers were discussed for properly mixing of combustion air and fuel gas. The produced mixture must be transported for combustion to burners or nozzles. In this chapter we will discuss the most important burners or nozzles. The burners or nozzles can be divided in two groups:
1. **Burners for open combustion chambers**.
2. **Burners for closed combustion chambers**.

Before these groups of burners are discussed, we will first briefly discuss flame stabilization and flash back prevention.

### Flame stabilization

The stabilization of a flame on the nozzle is a question of balance where the forward flow of the mixture and the reverse motions of the flame front (called rate of flame velocity or rate of flame propagation) are the same. At a certain flow rate, the flame front velocity will exceed the mixture velocity and the flame will then travel upstream and enter the mixer tube, causing an explosion. If the forward velocity of the mixture exceeds the reverse velocity of the flame front, the flame will be lifted off the nozzle (blow-off), causing uncontrolled combustion or even flame extinction (explosion danger).

In practical burner applications the forward velocity of the mixture will always be much larger than the reverse velocity of the flame. The reason for this is that any burner must have a turn-down ratio. This means that at minimum burner capacity the forward velocity of the mixture may be the same as the reverse velocity of the flame (flame speed). At higher capacities however, this will mean an always greater velocity of the mixture to that of the flame.

To prevent any flash back (flash back occurs when a flame front moves back into a burner nozzle), in practice a minimum differential pressure is recommended between the mixture manifold and that of the combustion chamber (see page E 32006.3 from Maxon).

For natural gas, propane or butane a differential pressure of 0.65 mbar is advised. The outlet velocity through the nozzle is at 0.65 mbar pressure much higher than the flame velocity. This means that even at minimum capacity blow-off or lifting of the flame from the nozzle would occur when no stabilization measurements are taken. The stability of the flame on a burner port is the result of the establishment of a predictable positioned zone in the system within which self-propagating combustion can take place. For ignition to commence, a mixture within the flammable range must be raised at least locally to a minimum temperature called the ignition temperature.

The most common stabilizing systems are:

a) **Flame stabilization by sudden enlargements**.

b) **Wake eddy stabilizations**.

c) **Continues igniting of the main flame by a ring of small ignition flames** (hold flame system).

d) **Partly circulation of hot gases**.

### Group a

Flame stabilising by sudden enlargement also called multiple stage internal design (see figure 44) is often applied to burners for closed combustion such as sealed in with refractory tile burners.
(see figures 45 and 46) or nozzle mixing type burners with sealed in refractory. The stabilization is caused by an eddy due to the sudden enlargement.

![Flame stabilization by sudden enlargement](image1)

**Figure 44:** Flame stabilization by sudden enlargement

![Sealed-IA burner](image2)  ![Sealed-in burner](image3)

**Figure 45:** Sealed-IA burner (Stordy-Hauck)  **Figure 46:** Sealed-in burner (Maxon)

**Group b**
The working principal of this system is in fact the same as described for group a. The bluff body causes a negative pressure and an eddy of the gases (see figure 47).
Group c
The continued ignition of the main flame by a number of small flames is a widely applied system in industrial as well as in domestic applications. The small ignition ports are giving an extra resistance to the mixture stream due to which the velocity of the mixture through these ignition holes will be much smaller. The outlets of these ports are coming in a small ignition chamber where a small ignition ring flame is formed.

Group d
Partly recirculation of hot gases is mostly found in industrial tunnel burners.
Prevention of flashback

As stated before, flashback will occur if the lowest forward velocity of the mixture is lower than the reverse velocity of the flame front. Most industrial burner manufacturers recommend a minimum differential pressure between that in the mixture manifold and that of the combustion chamber or space into which the burner fires. The recommended minimum differential pressures are:

- for natural gas, propane and butane: 0.65 mbar (6.5 mm WC)
- for manufactured gas: 1.1 mbar (11 mm WC).

See figure 50 and procedure following for suggestions on method of measurement of minimum pressure differential which is based upon the type of installation.

a) When firing into a combustion chamber operated at a balanced to slight positive pressure (0 to +1.5 mm WC)
(As in heat treating of melting furnaces fired open port nozzles of sealed nozzles.)

One leg of the U-tube of manometer should be connected to the air/gas mixture manifold at a point near the nozzle farthest removed from the mixer.
The other leg is open to the atmosphere as shown in figure 50a.
b) When firing into a combustion chamber operated with strong draft (-1 to -15 mm WC) (As in boilers, rotary driers, or barrel-type or drum-type air heaters on suction side of fan.)

One leg of the U-tube or manometer should be connected to the air/gas mixture manifold at a point near the nozzle farthest removed from the mixer. The other leg should be connected to a piece of tubing which may be inserted into the combustion chamber to sense the draft or suction as shown in figure 50b.

c) When firing into a combustion chamber operated at a strong back pressure (+1.5 to +50.0 mm WC) (As in scroll-type air heaters or special processes with externally created back pressures.)

Same general arrangement is used as shown in figure 50b. One leg of the "U-tube is connected to the manifold and the other one senses the back pressure in combustion chamber.

Burners for open combustion

Examples of open combustion are:
- A nozzle or a number of nozzles under a kettle or tank (reservoir).
- Infrared burners in the open.
- Line burners for air heating.

Essentially these burners are cooled by the air surrounding the burner. Extra care is needed in those cases where these burners are applied in closed combustion chambers. The burner and the mixture supply piping should than be cooled to prevent that at any spot inside the burner the ignition temperature of the air/gas mixture is reached.

The ignition temperature of some air/gas mixtures are:

<table>
<thead>
<tr>
<th>Gas</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>560-670</td>
</tr>
<tr>
<td>Propane</td>
<td>477</td>
</tr>
<tr>
<td>Butane</td>
<td>482</td>
</tr>
<tr>
<td>Town gas</td>
<td>500</td>
</tr>
</tbody>
</table>

Beside the above mentioned heating by the combustion chamber the burner housing will also be heated by the radiation of the flame and by the hold flame.

Line burners burning open air will reach a temperature over 200 °C during burning.

In general, burners for open combustion chambers can work in a surrounding of above mentioned ignition temperatures minus 300 °C. For propane this means that a surrounding of 177 °C is a practical maximum.

The next burners for open combustion chambers will be discussed:
- The so called sticktite nozzles;
- Special burners for spot heating;
- Line burners to be fed with a stoichiometric gas/air mixture;
- Radiant burners.

The burners for closed combustion we will discuss are:
- Sealed-in also called tunnel burners;
- Some radiant burners.

Sticktite nozzles
A very well known burner for open combustion is the sticktite nozzle. The sticktite nozzles produce a very stable flame. At mixture pressures over 40-50 mbar these nozzles are stable. Due to this a turndown ratio of 10:1 is possible. As described for stabilization these nozzles are provided with a ring of hold flames. The hold flame is fed through a number of small ignition ports. For draft conditions or mixture pressures over 20 mbar a better hold flame is needed than for balanced or overpressure conditions.

For draft and high mixture pressure conditions 8 or more ignition ports are needed.

Since a strong hold flame will heat the nozzle tip too much additional heating of the nozzle from the surrounding should be prevented. The nozzles can be fed with any of the described mixers. Sticktite nozzles are applied for bakery ovens, for immersion tube applications, melting ovens, furnaces. In figure 52 the flame length at different capacities is indicated.

Most of the sticktite nozzles are made from cast iron. For very high temperature applications (1000 °C and higher) sticktite nozzles with alloy tip or ignition ring are available (see figure 53).
For extremely high temperature operation (1300 °C or higher in furnace) two-piece sticktite nozzles as illustrated at right are available. The nozzle body, which is not exposed to radiant heat, is made of cast iron. The replaceable ignition ring or hood is made of heat-resisting chrome-nickel alloy.

Figure 53: Sticktite nozzles for high temperatures (Maxon)

Sticktite nozzles are available in sizes from 1/2” with a maximum capacity at 30 mbar mixture pressure of 17 kW through 811 nozzles with a capacity at 30 mbar mixture pressure of 4100 kW (see selection tables figure 54 and 59).
In normal cases the sticktite nozzles should be fed with a stoichiometric mixture. Some makes furnish special types sticktite nozzles for a 40% premix gas/air mixture (see figure 60).
Secondary air for combustion is then needed, due to which 40% premix can only be applied for draft applications.

Figure 55: Sticktite nozzle with spark and pilot (Eclipse) Figure 56: Sticktite nozzle with spark ignition and pilot (Maxon)

All programs do deliver sticktite nozzles complete with pilot, spark ignition and flame rod for flame sensing.
When sticktite nozzles are to be fired through fire brick walls into ovens, furnaces or combustion chambers a space should be made between the end of the nozzle and the furnace wall depending on the draft available and the secondary air needed for complete combustion. In general the applications are used for rather low temperature furnaces (600 °C).
Figure 54
Figure 57: Sticktite nozzle firing through fire brick wall (Eclipse)

Figures 58 and 59 are showing a typical selection table and graph as they can be found in industrial burner catalogs.

Figure 58: Capacity table for sticktite nozzles (Stordy-Hauck)
Figure 59: Capacity selection graph for sticktite nozzles (Eclipse)

Note: The capacities can be doubled with nozzles operating with 40% premixing. The maximum mixture pressure for 40% nozzles with pipe sizes 1/2”, 3/4” and 1” may not exceed 5 mbar.

Figure 60: Sticktite nozzle with ambient air supply holes (Eclipse)

Figure 60 shows a sticktite nozzle which can operate on 40% premixed air/gas mixture. Due to the draft conditions under which these types of nozzles must work, ambient air is sucked in through holes made in the outline of the nozzle. This air will be supplied to the air/gas mixture in the
recess around the main burner, thus making this mixture flammable (40% premix air/gas mixture can riot burn). The supply of ambient air will further cool the nozzle tip.

**Spear flame sticktite nozzles**

These nozzles are designed to produce a sharp spear like flame and are used for open firing. The burners are applied for heating which is needed in applications such as soldering, glass working, laboratory work etc.

![Figure 61: Spear type sticktite nozzle (Selas)](image)

These nozzles are normally used for open firing either individually or in groups where a focused or spot heat is required.

**Special burners for spot heating**

Sometimes heating is needed on localized areas of work pieces like flame hardening, flame annealing, brazing and soldering, spot heating etc. These special burners can produce flame temperatures up to 1540 °C and blast velocities up to 180 m/s. With these types of burners very short heating times can be achieved. The direct flame burners are basically miniature refractory lined high velocity type burners. These burners are fed with a premixed mixture of combustion air and gas at a maximum mixture pressure for natural gas of about 60 mbar.

The basic operating principles of the superheat burner are illustrated in the accompanying cut-away drawing.

Gas and air mixture, generated in combustion controller equipment, burns inside the burner, from numerous precision ports, in a close-tolerance ceramic structure (A). various port patterns and assembly methods are employed, depending upon type, size an expected service of the superheat burner.

Combustion proceeds along, and in contact with, the surface of a preformed high-temperature insulating refractory lining (B) capable of withstanding more than 1650 °C. This lining is closed-in at the nose to form a nozzle of blast-opening (C) of appropriate shape.

The walls of the lining (generally corrugated) attain white-hot incandescence and intense radiation plays from wall to wall across the travel of the gases, accelerating the combustion reaction.
The superheated blast or tongue (D) issuing from the outlet nozzle and directed at the work at close range is undiluted by secondary air.

The entire assembly is compact and durably encased in a shell (E) attached to a plenum chamber (F) behind the ceramic part-plate structure. The pipe connection (G) is a standard pipe thread available either male (as shown) or female.

Figure 62: Superheat spot burner (Selas)
Some other shapes of spot heating burners are shown in figure 63.

Figure 63: Sam spot heating burners (Selas)
Line burners to be fed with a stoichiometric gas/air mixture

These burners are also often called linear multiple port open firing burners.

Linear multiple port open firing burners have a row or rows of main flame jets, paralleled on each side by a row of small pilot holes in a groove or recess which provides room for the pilot gas expansion and the flames of the pilot gas, and protects them from being extinguished by drafts. This type of burner is used where a continuous line of flames is desired or where a considerable volume of gas is to be burned in a small flame size over a larger area. Ignition for these burners can be at one central point since the pilot flames light each other and each section lights the other. This type of burner in various forms is widely applied to low temperature applications such as air heaters, kettle heating and tanks and similar low temperature applications.

Figure 64: Linear multiple port open firing burner to provide a line flame

The line burners can be fed with all described mixer systems for maximum mixture pressure of about 30 mbar giving a maximum turndown ration of 7:1. There is a great variety of premix line burners on the market. Most of these line burners can be adapted to about any capacity per foot of burner (30 cm burner length) by making the burner port drilling in numbers and diameter in accordance to the needed capacity. The normal capacity range per foot of burner is between 1.7 kW to 330 kW. Most of the line burners are provided with two ignition under which small ignition ports are drilled in the housing.

Due to the fact that the mixture of combustion air and fuel-gas will be heated inside the line burner sections, the following maximum housing surrounding temperatures are advised:
- Natural gas 260 °C
- Propane gas 180 °C
- Butane gas 190 °C
- Towns gas 200 °C (if H2 is present in the fuel gas lower surrounding temperatures should be selected)

Some types can be provided with special alloy ignition rails which allow air temperatures up to 350 °C. Burners can be safeguarded at any point by a UV scanner or a flame rod. UV scanners are recommended for applications above an ambient temperature of 200 °C.

For air heating applications it is recommended to have an air velocity of about 10 m/s passing the burner. Most burners can withstand up to 18 to 20 m/s. All line burners are made of cast iron and are available in a variety of shapes to fit the individual job: straight sections, T-sections, elbow-sections, cross-sections etc.
For some applications see figures 65a, 65b and 65c.

**Localized flame heating for continuous conveyor processes**
Line burner assemblies are often used for open-air or semi-enclosed spot heating applications in which work is carried through the burner flame on a continuous conveyor. Glassware can be glazed, metal edges preheated, or small parts flame-annealed by passing them through the line burner flames.

![Figure 65a](image)

**As combustion grill beneath kettles, tanks and vats**
For kettles and tanks which cannot be heated by the more-efficient immersion-tube method line burner may be used. Even distribution of heat is secured below the kettle or tank. The maximum temperature in the housing surrounding the kettle should not exceed 400 °C.

![Figure 65b](image)

**Direct-firing of core ovens and industrial drying ovens**
Where the cost of a complete gas-fired circulating air heating system is not justified, installing a line burner assembly down each side of the oven will give even distribution of the heat input down its length and eliminate cold spots. Oven temperatures up to 250 °C may be secured.

![Figure 65c](image)

Some general line burner constructions with different flame retention systems are described further.

a)Line burners with ignition rail (figure 66)
The working of the flame retention is similar to that of the described sticktite nozzles. A continuous ribbon of igniter or pilot flame beneath the ignition flanges constantly lights the air/gas mixture issuing from the main burner ports. The flame is held tight upon the face of the line burner.

Alloy ignition rail is available for air return temperature up to 350 °C.

These burners are in general able to have a turn-down ratio of 4:1 to 7:1 depending upon the back pressure conditions. The heat release of these burners can be selected between 3 and 145 kW per 30 cm section. The most common available burner sections are shown in figure 67.

For ignition and safeguarding an ignition burner and for most cases a flame rod is applied. See figure 68.
The working of the flame retention is based on small flames burning against a sloping placed ignition plate or rail or for some applications a combination of a rail and a plate. This system guarantees constant lighting of the air/gas mixture issued from the main burner ports. The ignition plates are made from alloy. Also this construction allows a maximum turn-down ratio of 7:1. The heat release of these burners can be selected between 3 and 145 kW per 30 cm section. The most common available burner sections are similar to those shown in figure 70.

Some examples of burner patterns are shown in figure 70.
A little different design is shown in figure 71. This burner called "Curtain burner" is a premix burner designed to provide a reducing flame at the entrance or exit of a furnace to prevent air from entering the furnace and causing an oxidizing atmosphere. These burners have an input of about 19 kW per 30 cm burner when operating with an air/gas ration of 3 to 4/1 and a mixture pressure of 10 mbar (rich). The flame length under these conditions is approximately 90 CM.

Flame retention is achieved by a design of interlacing jets which assure continuous and constant ignition along the entire length of the burner. In this design no ignition rails, plates or baffles are needed. These line burners are specially designed for air heating since the flame pattern is different (V-shaped), see figure 73.
Since there are no ignition rails heated by pilot flames these types of line burners can stand higher air recirculation temperatures than other described line burners. For these burners a maximum return air temperature of is recommended depending up the type of fuel gas. If there is H, in the fuel gas mentioned temperature should be selected lower.

The turn down ratio of these line burners is somewhat higher due to the fact that the burner can be provided with higher mixture pressures up to 30 mbar giving a turn-down ratio of 10:1. The maximum capacity per 30 cm line burner length is about 160 kW with a minimum of 16 kW. These burners are also available in a number of shapes like straight, elbow, T section and cross section as shown in figure 75.

Figure 74 gives some principle sketches of recirculating and fresh air heating systems.

From figure 74 can be seen that line burners can be located on either the pressure side of a circulating fan (location A) or on the suction side (location 3) to heat flows of air moving at velocities up to 20 m/s. Since line burners are mounted directly in the stream of moving air all of the heat release from the combustion is picked up by the air. All the described line burners will perform well in return
air with high percentages of inert gases due to the fact that the burners are fed with all needed combustion air. When using a line burner for air heating the heat will be well distributed over the duct area (see figure 75).

Figure 75: Line burners assembly containing 18 linear units of burners mounted in an air duct (Maxon)

d) Line burners for heating narrow spaces (ribbon burner)
These burners are applied for those applications where a narrow space on a product must be heated by flame impingement such as continuous heat processing applications. These burners are further applied for soldering and brazing heating tin pots etc. and in general for glass, printing, textile and wire industries.

Some typical applications include (see also figure 73):
- Preheating lehr & furnace belts
- Ink drying on printing presses
- Surface & edge fire-polishing
- Glass forming
- Wire annealing & preheating
- Local annealing or tempering
- Textile drying, singeing, tentering
- Calender and other roll heating
- Soldering & brazing
- Curing & setting coatings on metal
- Shell & cartridge case heat treatment
- Heating tin pots
- Heating motor commutators
- Curing storage battery plates
- Heat treating plastic webs
- Furnace flame curtains.

The ribbon burners has an assembly of perforated refractory ribbon plates for maximum flame retention and resistance to thermal attack. The plates are precision molded from compounded heat shock resistant ceramic material and are kiln fired. They are laminated to form a practically monolithic structure with precise ports which do no distort, corrode or "grow". These ceramic assemblies are firmly encased within sturdy cast iron manifold sections, with either bottom or end-inlet connections (see figure 76 and figure 77).
These types of line burners can be supplied in many different sizes for all sorts of flame lengths, flame width and heat capacities. The maximum mixture pressure for these burners is about 25 mbar.

Filaments for lamps are preheated ahead of drawing dies, as shown here. Fine sewing threads are singed in multiple strands. Copper alloy wire is heated in this way for annealing.
Webs are dried, cured or preheated by directing the burner flames against the passing material. Flames are sufficiently uniform to be successfully used for textile singeing. Electrical static is discharged by flame conduction.

Parts of many shapes and materials are handled on conveyors as shown. Fabricated pieces of steel, glass and nonferrous materials are heated for hardening, tempering, annealing or hot forming.

Air is heated for many purposes by inducing (or forcing) it over ribbon burners within insulated chambers. Applications include drying, enamel baking, food preparation, curing and other similar uses.

Conveyors of ovens, furnaces and lehrs are preheated to offset effects of cooling during return travel. This practice increases production and reduces thermal shock to previously heated ware.

Rolls for calendering are frequently internally gas fired. This arrangement of ribbon burners provides a suitable means of obtaining uniform lateral heat distribution. Rolls without internal accessibility may be externally fired.
Wire is conveniently cured after coating or otherwise treated by conveying it vertically through special ribbon burners. Multiple strands are normally heated simultaneously. Burner manifolds are retractable for accessibility.

Glassware must be fire-polished or "glazed" to eliminate sharp moulded edges that might injure the user. Glazing is frequently performed by fusing the sharp edges while the ware is continuously conveyed through ribbon flames.

Figure 78: Applications (Selas)

Radiant burners (infrared)

Many materials absorb heat faster and more efficiently from an infrared source than from convection or conduction heat sources. For this reason infrared burners were developed for industrial use. Ideal processes for infrared heating are in drying, curing, annealing etc. Very often infrared heating is applied as a production booster on existing installations. For instance infrared heating can be applied directly to the moving product in continuous strips, sheets or webs before it enters the convection dryer. This may increase the production capacity by 25% or more.

Radiant energy transfer

In radiant drying heat is transferred from a gas or electric infrared heat generator through an air space to the product. There are several factors that affect the rate of radiant heat transfer: the temperature and nature of the emitting surface, the temperature and absorption characteristics of the product; the atmosphere between the emitter and absorber and the geometrical view factor due to shape and location of the object being dried with reference to the heater.

The primary advantage of radiant heating is the high heat transfer capability over a range of conditions. For heating and curing of organic coatings, substrates and objects, radiant energy penetrates directly into the materials which often are poor conductors of heat energy. For drying of most solvent and water based emulsions, glues, coatings and wet materials, radiant energy penetrates the material and vaporizes the solvent molecules and greatly increases the overall drying rate. The drying process becomes less heat transfer controlling and more mass transfer
controlling. The conventional constant drying rate period is extended considerably to lower moisture content levels and the drying rate is much higher than rates obtained by conventional methods.

**Radiant heat transfer in more detail**

The total amount of radiant energy being emitted can be calculated from the following relationship:

\[
Q = A e k T^4
\]

where \(Q\) is the energy emitted, \(A\) is the area of the emitting surface, \(e\) is the emissivity of the material from which the emitter is made, \(k\) is the Stephan-Boltzman constant law defines emissivity as the ratio of the emission of an ideal black body radiator to a non-block body radiator such as a ceramic or a metal.

Thus the total energy emitted per unit of area will vary with the emissivity of the source, its material of construction and the fourth power of the absolute temperature of the emitter. For a given emitter, the energy produced will therefore depend solely upon the temperature at which it is being operated.

For practical applications above relationship becomes:

\[
Q = A e * 5.73 \times 10^{-12} (T_r^4 - T_s^4).
\]

In this formula \(T_r\) is the absolute temperature of the source in K and \(T_s\) is the absolute temperature of load or receiving object in K. \(Q\) is expressed in W/cm².

**Wavelength variation**

Distribution of radiant energy by wave length from a radiant source is dependent upon the temperature of the radiant source (see figure 79). A fact that is apparent from examining these curves is that the peak of the power spectral curve shifts to shorter wave lengths, with increasing temperature. This is known as the Wien Displacement Law which predicts the temperature at which the maximum percentage of energy can be found for any given wave length. The Wien Displacement Law can be shown in the next formula.

\[
l = \frac{\text{Wien constant}}{\text{radiant temp. in K}} = \frac{2896}{K}.
\]

\(l\) is the wave length in microns at which maximum radiation will occur.

The Wien Displacement Law has often been misused in the attempts to select the right source temperature where energy radiation is maximum at a predicted wave length. By only using the displacement law the total energy input has been neglected. The amount of radiant energy at any wave length always increases at higher temperatures. This can be illustrated in figure 79.
Let us take as example a material which absorbs most energy between 5.5 and 6.5 microns. From table figure 80 can be seen that a radiant source of 800 °C will emit 7.6 in the wavelength between 5.5 and 6.5 microns. At a radiant temperature of 980 °C at the same wavelength only 5.99% is radiated. The amount of energy is at 800 °C

\[
7.58 / 100 \times 272 = 20.72 \text{ MJ/m}^2 = 0.57 \text{ W/cm}^2
\]

The amount of energy at 980 °C is:

\[
5.99/100 \times 507 = 30.37 \text{ MJ/m}^2 = 0.84 \text{ W/cm}^2
\]

Calculations are made at \( e = 1 \).

<table>
<thead>
<tr>
<th>Source temperature</th>
<th>800 °C</th>
<th>980 °C</th>
<th>1200 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave length range</td>
<td>Total energy</td>
<td>272 MJ/m²</td>
<td>Total energy</td>
</tr>
<tr>
<td>0.0-0.7</td>
<td>0</td>
<td>0.01%</td>
<td>0.03%</td>
</tr>
<tr>
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<td>4.89%</td>
<td>9.46%</td>
</tr>
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<td>25.44%</td>
<td>32.76%</td>
</tr>
<tr>
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<td>9.66%</td>
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<td>5.99%</td>
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</tr>
<tr>
<td>8.5-</td>
<td>10.85%</td>
<td>7.44%</td>
<td>4.92%</td>
</tr>
</tbody>
</table>

Figure 80 energy distribution & total energy vs. wavelength: total energy, %; total energy MJ/h/m² \((e = 1, T_s = 293)\)

From above example it will be clear that at a given wavelength range maximum energy will always be available at the highest temperature.

Absorption characteristics
When radiant energy is to be used as a source of heating, one must also consider the radiation absorption characteristics of the object to be heated as well as the design of the heater. As emitters vary in their ability to produce the right amount of heat at a desired wavelength, so the materials which are to be heated vary in their ability to absorb or to convert the radiant heating energy into thermal energy.

The radiant energy absorption characteristics of water films of various thicknesses are shown in figure 81.

![Infrared absorption spectra for thin layers of water showing the effect of thickness](image)

For drying wet paper most likely a water layer of 0.01 mm can be expected. It would then appear that radiant energy sources having an emission wavelength of 3 and 6 microns should be used. From above it will however be understood that for most concentrated energy emission per cm² an infrared heater will highest possible temperature should be selected. However if the total radiation or emission pattern is known together with the absorption pattern, the difference between emitted and absorbed energy can be estimated. This energy will flow sideways out of the radiant heater. In practical installations this energy is taken away by an exhaust fan and utilized in the convection dryer part as make up air.

**Equipment and types of radiant burners**

The interest in infrared heating developing over the past thirty to forty years has resulted in many types of infrared generators. They can be divided into two general classifications, by the type of fuel used (fuel gas and electricity). The gas-fired generators can be classified in 7 categories:

1) Radiant tube burner where the air/gas mixture is fired into the tube, the surface of which becomes the radiator. Figure 82.

2) A premix burner such as the spiral flame which as the result of controlled velocity spreads the flame over a large flat surface generating radiant heat. Figure 83.

3) Surface combustion burners which utilize a porous refractory for radiation on which a gas/air mixture burns. Into this same group would fall drill port ceramics, and metallic screen. Figure 84.

4) Direct fired refractory burners which utilize the impingement of the gas flame on the refractory and produce the highest intensity, flux density radiant. Figure 85.

5) Catalytic burners that use a catalyst to oxidize gas at low temperatures. Figure 86.

6) Flat flame burners. This burner will be discussed in the chapter about nozzle mixing burners (chapter IV). Figure 87.

7) Matrix type comprising a high emissive power ceramic refractory fiber bound together to form a three dimensional fiber matrix. Some makes are developing alloy matrixes (see figure 95).
The three general classifications of the above types of emitters are:

1) The low intensity type being the catalytic burners and some radiant tubes which operate with a normal radiation of from 11.3 to 34 MJ/m²/h of radiant surface. The source temperatures usually run in a range of 400-480 °C.

2) The medium intensity types which cover the porous, refractory, drilled port ceramics and metallic screens usually operate at 227-350 MJ/m²/h with face temperatures ranging from 760-870 °C.

3) The high intensity burners being those of the impingement type usually operate in the 450-970 MJ/m²/h with an average face temperature of 980-1200 °C.

There are various types of gas burners as mentioned before available for radiant heat applications. There is very little radiant energy in a gas flame. A rule of thumb is that
approximately 10 to 15% of the available energy in a gas flame is in the form of radiant energy. To obtain substantial amounts of radiant energy, it is necessary to take the energy of combustion and convert it through some means into radiant energy. In the burners described below the gas flame has been arranged to impinge against a ceramic block. By conduction and convection most of the energy of the flame is transferred to the ceramic block. The block in this way forms a link and serves to convert the energy of combustion into radiant energy.

In practice this is achieved by two different methods. The first method is by the "impingement type burner" where the refractory is heated by impingement of many small gas flames.

The second method, the "grid type", is to force the air/gas mixture through a porous refractory, burning on the surface of the refractory and through the use of a reverbatory screen to bring that refractory to a temperature of 760 °C to 920 °C.

Ceramic impingement burner

The impingement type of infrared burner delivers a combination of infrared energy and convection heat transfer, the last by utilizing the hot flue gases produced by combustion to flow over the product. Any of the described mixing devices can be used to supply a fully premixed mixture at a maximum pressure of maximum 22 mbar to the burner manifold. A turndown ratio of 20:1 can be achieve with most applications. The gas/air mixture passes out of the manifold through ports in the burner body and is directed by an alloy deflector plate into the refractory grid. Between the ribs of this high temperature refractory grid, small flames develop the heat that brings the refractory grid to radiant temperatures.

This type of radiant burner can perform an average higher temperature than the porous ceramic type (grid type). The temperature which can be reached is about 1100 °C at 20 mbar mixture pressure. At 0.5 mbar mixture pressure a face temperature of about 450 °C can be expected. Only a part of the energy is infrared radiation. A large part is released as hot combustion gases for convection purposes.

These gases are having a temperature of about 1050 °C. When down firing these gases may cause problems to connections such like as rod wiring. Down firing radiant burners are spaced about 50 to 150 from the product to be heated.

The burners are designed to function in open systems. The temperature should not exceed about 300 °C for reasons as stated before. Many makes provide sections in different sizes like 6", and 12" sections and elbow sections shapes like double and single grid burners.

Some usual line burner constructions on the market are described.
Figures 88 and 89 are showing normal so called double grid impingement burners. Rows of small ports direct flame against the curved block surface heating them to temperatures of maximum about 1150 °C. These burners produce a high intensity, concentrated radiation. In addition the curvature of the refractory directs a hot, turbulent stream of exhaust gases towards the product giving a good heat transfer. The refractory fins are also needed to produce flame retention and to give complete combustion. The space between two fins can be compared with small combustion chambers. If these fins are constructed to high they might tend to break from thermal expansion and contraction, and in time require replacement. Figure 90 shows a double grid model from which one gives a more concentrated stream of exhaust gases than the other. With the first type the exhaust will travel from the face of the burner about 250 mm before losing momentum and rising.
The ceramic tile or grid type radiant burner

A low excess air mixture ($n = 1.05$) of combustion air and fuel-gas is supplied at a maximum pressure of about 8 mbar to the burner manifold. Any of the described mixing devices can be used. These types of burners perform best with all combustion air supplied (100% premix).

Burner manifold and head are of cast iron construction with ceramic burner grid and Inconel reverberatory screen. The ceramic burner grid possesses many small holes. The Inconel screen is mounted at short distance.
From the burner manifold gas is supplied into the small holes of the ceramic grid. The gas/air mixture is heated and ignites in the small holes. The end of the many small flames is between the ceramic grid and the screen. A hold flame construction is not needed. The mixture flow velocity is low due to the large surface with many small holes and the rather low mixture pressure. The ceramic surface temperature is over 900 °C higher than the ignition temperature of the air/gas mixture.

The sintered ceramic material has a sponge-like structure - with many small empty spaces giving a poor conductivity for heat. This causes a quick heating up to the surface and also a rather cool mixture supply side. This inner side is also cooled by the supply of the mixture. The gas/air mixture burns just at the inside of the many small holes and on the surface against the screen (see figure 92) causing also the screen to glow.
The screen has two purposes:

a) It reflects a part of the produced radiation giving a higher ceramic surface temperature.

b) It prevents that any unburned gas/air-mixture will pass.

The burners are designed to function in open systems. The surrounding temperature should not exceed about 310 °C for reasons as stated previously. Burner face temperature at maximum input when firing in the open is approximately 900 °C. At higher face temperature reduced burner life may occur. High ambient temperature and/or high reflection of the heated surface will increase burner face temperature. Burner input should in these cases be reduced to bring back the surface temperature to about 900 °C. Many makes deliver burner sections in different sizes which can be combined to a row of infrared burners or a bank of rows. See figure 93.

The shown burner has the mixture manifold separated from the burner head. This feature allows the changing of burner heads on the job site without taking the complete burner out of the row or panel. Burner manifold and head are of cast iron construction with ceramic burning grid and Inconel reverberatory screen. Each burner head is equipped with an adjustable orifice for controlling the mixture flow. This permits individual adjustment for exact balancing of input over a long row of burners or provides a method of shutting off individual burners in a row or panel.
Figure 94: Installation with grid type burners fed with low pressure mixers (Eclipse)

Since the holes in the ceramic grid are small, these burners are very sensitive for dirt particles in the combustion air. For these reasons it is extremely important that the combustion air blower is equipped with an adequate inlet filter.

The maximum capacity of a grid type burner section having face dimensions of 300 x 150 mm = 450 cm² is about 5,86 kW (5040 kcal/h). Mixture pressure is about 8,4 mbar.

With the next formula the total radiation in Watt/cm² can be calculated:

\[ Q = 5.73 \times 10^{-12} \times e \times A \times (TR^4 - TS^4) \]

- \( Q \): total radiation in Watt
- \( e \): emission coefficient which is for the ceramic material 0,8
- \( A \): burner radiation surface area in cm², which is 450 cm²
- \( TR \): temperature of the ceramic surface in Kelvin
- \( TS \): temperature of the surrounding in Kelvin

Knowing that the burner face temperature is 870 °C (1144 K) and the surrounding temperature is 20 °C (293 K) the radiant energy per cm² can be calculated:

\[ P = 5.73 \times 10^{-12} \times 0.8 \times 450 \times (1144^4 - 293^4) = 3518 \text{ Watt.} \]

Radiant efficiency is given radiant energy divided by supplied energy 3518/ 5860 x 100 = 60% which is a rather high efficiency.

Radiation per cm²:

\[ 3518/ 450 = 7.82 \text{ Watt/cm²} \]

The radiant wavelength (l) can be calculated as follows:

\[ l = \text{Vienna constant/radiant temp. in Kelvin} = 2896/ 1144 = 2.53 \mu m \]

Some industrial applications

Non-wovens/disposables

This product can be placed between paper and textiles and both industries make them. They are manufactured by various processes but certain basic steps are made by all manufacturers. Cellulose fiber is placed on a conveyer and coated with resins. The resins are set forming the sheet
by the use of radiant burners. The final curing and drying is done on conventional dryers or steam cans. When the finished product is used to manufacture hospital supplies, such as operating room gowns, draw sheets etc., it is treated with fire retardant and moisture repellent solutions. Gas radiant burners can then be used to complete drying in this process.

Textile industry applications
The textile industry is one of the largest in the world. The consumption in this industry is mostly that of drying, for which steam has been used extensively. With the introduction of new products, new techniques and the necessity of greater speed for more economical manufacture, it is of prime importance to investigate drying systems that may be more versatile.85 The application of IR-burners consisted entirely of using burners for supplemental heat in such uses as textile Slashers, pre-dryer for fabric ovens and fabric singers.

Ceramic and tile, ceramic industry
The ceramic and tile industry has utilized gas infrared burners for some years. Primarily in floor and wall tile. These tiles are pressed or formed and contain from 5% to 12% moisture, usually around 5% to 6%. This moisture must be removed before the tile is fired in the kiln. This application lends itself well to the IR-burner. In this drying process "soak time" must be allowed for the steam, as it is generated within the tile, to migrate to the tile surface to be released, or the tile will itself explode.

Glass
Impingement type infrared burners have been used in the glass industry in various locations. The cup type such as Selas has been used in the walls and ceilings of glass lehrs. The temperatures in the lehrs are usually too high for the infrared type burner, however, this type of burner has been used successfully in the preheating and cooling down of glass entering and leaving lehrs.

Some glass companies manufacturing bottles have two processes to the finished bottle in which gas infrared burners can be used successfully. One is a sleeve of foam plastic which replaces the label and gives the bottle an additional insulating factor as well as a certain amount of protection from breakage. In this process the bottles are preheated to approximately 2000. A sleeve is slipped onto the bottle and the bottle is then run through a convection oven, drawing its heat from the infrared flue products to shrink the plastic sleeve on the bottle. This process is basically owned by Owen's Illinois and is called "Plasti-Shield".

The second process is being pursued by many glass companies as well as the OEMs supplying them ovens. This is a plastic coating which will basically prevent the bottle from exploding and should the bottle become damaged and break, it would then retain the breakage within this plastic coating.

Matrix type with ceramic fibers
The heating element is a porous pad, about 2.5 cm thick, which is comprised of high emissive ceramic refractory fibers, bound together to form a three dimensional fiber matrix. This matrix is then clamped onto a plenum which has an inner chamber and perimeter outer chamber. A stoichiometric ratio of fuel gas and air is introduced into the inner chamber at a positive pressure of 5-15 mbar. This gas/air mixture flows through the porous pad and is ignited. Since the gas/air mixture velocity at the outer surface of the porous pad is, by design, less than flame speed, the actual combustion takes place within the outer surface of the pad, about 3 an deep, in the presence of thousands of fibers /cm2. The low gas velocity and large fiber surface area contribute to the very high conversion to radiation efficiency achieved by these infrared generators. Flash back or backfire is prevented by the inherent thermal equilibrium of the reaction. A uniform surface temperature and high radiant heat flux is thereby maintained.
The hot exhaust gas purges the surface pores and forms an oxygen depleted gas blanket over the panel, thereby preventing foreign particles or contaminated vapors from clogging the heating pad. Since only the outer layer (less than $0.7 \, \text{kg/m}^2$) of fibres is heated, there is little thermal mass and the surface quickly cools when the gas is turned off. These infrared burners operate at face temperatures normally between 600 and 870 °C. For special purposes a face temperature of 1100 °C can be reached. The matrix face emits infrared energy in the peak wavelengths of 2.5 to 3.3 microns with power densities of 2.92 to 8.38 kcal/cm²/h (3.4 - 9.74 Watt/cm²).

They can be applied for many gases such as propane, butane, natural gas etc. Maximum fuel input is above 12.7 kcal/cm²/h.

Figure 95: Matrix type radiant burner (Stordy-Marsden)

Applications
The Matrix infrared system has been used in a wide range of applications including heating, curing, drying and annealing. It has found particular value in the thermal processing of continuous webs (textile, plastic, non-wovens and paper) because the radiant flux can be rapidly modulated to match machine speed or desired product condition (temperature, moisture content, curing condition).

Some other types of industrial grid type infrared burners

On the next pages some other makes of premix infrared burners are discussed. They are discussed separately because they are in general applied only for certain applications.

The group Schwank-Gogas radiant burners
These burners are working similar to the described radiant grid type burners with glowing ceramic plate. Principles of the working of such burners is shown in figure 96.
The ceramic plate will get a maximum temperature of 850-900 °C. The backside of the plate is maximum 100 °C.
At 850-900 °C the maximum radiant intensity will be at 2.6 microns. This is well within the region where the maximum absorption is found for many materials. These burners are very often applied in continuous ovens to dry painted products. Paint has the maximum absorption between 2.8 and 6 microns.

In many installations this type of radiant burners is applied for industrial building heating (see figure 98). For industrial applications these infrared burners are always premix supplied with a just over stoichiometric mixture.

Figure 96: Principles of Schwank and Gogas type burner

Figure 97: Atmospheric radiant burner (Schwank)

Figure 98: Application of radiant heaters for heating buildings
The premixed burners can reach surface temperatures up to 930 °C and can be turned down to about 500 °C.

**Krieger infrared radiant grid type burner**

In paper making industry infrared heating can very well be applied for boosting paper production. From absorption figures for water and paper (see below) can be seen that 2 and more microns are needed for best absorption.

A combination of these curves can be made for a damp paper. It may be further considered that the radiation emitted at short wave lengths will not be absorbed by the surface of the paper, but will penetrate inside the sheet where it is reflected by the fibers, hence increasing the internal temperature of the sheet. The installation of infrared radiant burners on paper making machines is governed by the following targets:

- increase of machine production;
- supply a particular quality of paper.

Radiant heat can be applied in the following places, see drawing figure 102.

Figure 102: Radiant burners on a paper machine

Wet end section
This section of the machine comprises the table and the presses. At this stage the pulp contains more water than dry matter (fibers) and the problem is to wring out or press out the maximum amount of water at the presses. The purpose of an infrared radiant heater is to heat the water and pulp that is generally cold, in order to lower the water viscosity. At lower water viscosity the pressing and drying effect of the press section will become more efficient. This means that the dry paper content at the inlet of the dryer gets higher.

Remarkable results have been obtained with this procedure particularly with medium weight board (10% more production).

Inlet drying section
It is interesting to heat the paper before it enters the drying section. Heating of the paper with infrared before it enters the fast drying-section means that evaporation can start on the first drying roll. It will give a gain in speed and a more efficient first and second drying roll.

Size press
The size press is often located at 2/3 of the drying section where the paper is at 70 to 90% bone dry. At the size press water will be added to the paper. For this reason it is interesting to plan infrared heaters at the exit from the size press.

Coating
This is the most remarkable application of infrared radiant burners. Coating consists of applying a watery coat containing mainly kaolin, but also binders such as latex, starch and other products in smaller quantities.

Once the coating has been applied, the water tends to penetrate into the paper, carrying the binders with it.

But, in order for the paper to be printable, the binders must be distributed uniformly in the coating and for this it is necessary to dry it rapidly through its entire thickness. Infrared radiant burners only can do this.

Operation of the burner, see drawing.
Gas and air are separately supplied to the burner. In the burner gas is supplied through a nozzle and air around the nozzle tip. The gas is than further mixed in a mixing pipe and supplied to a sort of plenum where it gets a very even mixture pressure. From here the gas is supplied by a large number of supply pipes to the combustion area where the mixture ignites and burns. The metal screen is heated by the combustion of the mixture and produces the radiation.

The velocity through the many supply pipes is much larger than the rate of flame propagation which means that flashback will not occur.
Figure 103: Construction of Krieger I.R.-burner

Figure 104: A single I.R. Krieger burner
Radiant tube type burner

The radiant tube burner will only briefly be described in this chapter because most of the radiant tube burners are provided with nozzle mixing burners which will be described in chapter V. Radiant tube burning is in fact closed combustion. This remark is made here because we are still discussing open combustion systems.

Indirect firing is essential for many heat treatment processes where the work must not come into contact with the products of combustion or the flame. There are a number of ways in which separation can be achieved, such as using a muffle to enclose the work, but in many cases this is not practical or desirable, especially when the process must be carried out in a vacuum or special atmosphere. The gas fired radiant tube offers many advantages as a source of indirect heating and has become firmly established in the metallurgical heat treatment field. The absence of combustion products in the chamber means that furnace wall linings last much longer and down time for rebrickling is greatly reduced.

A radiant furnace radiates heat to the work from one or more radiant tubes inside which the process of combustion takes place so that the hot gases are completely contained inside the tube. Heat is thus given up to the inside wall of the tube, conducted through the wall and radiated to the work in de furnace. Separation of the work from combustion gases is thus achieved. In some cases, where a special atmosphere is recirculated within a furnace, some of the heat is also dissipated by convection, but generally the main function of a radiant tube is that of a radiant heat source.

Most of the heat treating furnace applications require temperatures in the range of 750 to 1000 °C.

Radiant tube temperature requirements are typically 50 to 100 °C higher than the furnace temperature. Heat fluxes delivered by metallic tubes are approximately Very modern recirculating single ended radiant tube has shown a heat flux of up to 32 kW/m2.

The tube life time is in between 1 and 3 years depending upon the application temperature.
Metallic tube life time will be reduced when they are continuously operating above 1000 °C. Due to this most heat treating furnaces for above 1000 °C operation are electrically heated.

The tubes are usually made of heat resistant metal and indeed the temperature limitation of this type of furnace is conditioned by the tube material. It must be emphasised, however, that without going to special materials such as ceramics, metallic tubes offer a wide range of temperatures, from 300 °C to 1100 °C, comprising a large range of industrial processes. It is necessary, however, in many circumstances, to use a tube material very near the critical temperature at which oxidation and creep become serious factors. To ensure a reasonable tube life this means that hot spots must be eliminated or reduced to the minimum and for this reason considerable research and development has gone on to--obtain more even temperature distribution along the length of tube.

Waste heat recovery can be achieved by either an external heat exchanger, or by a recuperator integral with the burner. The integral system avoids the losses associated with external pipe work leading to central recuperation, but there is the problem of air density variation as the burner warms up. Often this involves air/gas ratio control equipment to compensate for this effect by back loading linked valves, or incorporating volumetric governor and relay combinations.

Efficiencies which can be gained with radiant tubes is about 40-70%. The burner inside these tubes is always of the nozzle mixing type. Since tubes are made of expensive alloy or ceramic material, it is important that no part of the tube will be damaged by overheating. This requires that the flame within the tube must release its heat at a uniformly high rate throughout the tube length. A delayed mixing flame accomplishes this requirement. To avoid a wasteful cool section at the burner end of the tube, a partial premix is incorporated into the burner. This produces a blue flame at the beginning (about the first 30 cm) until the luminous flame develops. Other systems will be discussed in chapter V.

Some modern designs are shown in the figures below.

![Figure 106: Some radiant tube designs](image-url)
Catalytic type radiant burner

This burner will only briefly be discussed because of the not completed development stage of this type of burner. Figure 107 shows the cross-section of a catalytic burner and figure 108 shows the burner face.

![Cross-section of catalytic burner](image1)

Figure 107: Cross-section of catalytic burner

![Catalytic radiant burner](image2)

Figure 108: Catalytic radiant burner

The principle of working of these burners is based or accelerating the oxidation of the fuel below the normal ignition temperature of the air/gas mixture with the help of adapted catalytic material. In these burners the fuel gas is oxidized without producing a flame with the help of the catalytic material below the ignition temperature.

The surface temperature of these radiant burners will reach between 400 and 480 °C (34 MJ/m² / h). To start the chemical reaction in the catalytic material the fuel gas should be heated to a reaction temperature which is accomplished by an electrical wire. During the working a part of the reaction energy is used for the preheating. The time to reach the maximum face temperature is about 3 to 4 minutes. The peak wavelengths are at 4 to 4.5 microns. An important feature about these catalytic radiant heaters is that due to the low combustion temperature extremely low levels of NO, are produced (0.1-1 ppm). Also the produced level of CO is very low (<0.1 ppm).

Premix Cup Type Radiant Burner

In those cases where a local heat is needed in selective areas or for heating moving webs of fabric, paper, vinyl etc. or a fast accurate direct radiant heat is needed etc. a broad program is available of adapted radiant burners.

These burners are in fact cup-shaped, ceramic precision combustion tools which radiate heat to work pieces intimately, without flame impingement. Fast and very controlled heating of a wide variety of materials is accomplished by these burners. In most cases these burners are placed close to the work pieces to heat them directly, allowing for more compact furnace structures. With these burners heat can be radiated to concentrated places. Operating principle: air/gas mixture enters the burner tube (see figure 109) and flows to the burner tip (1). After the mixture passes through the tip's threaded refractory orifices (2), it is distributed radially and burns within the refractory cup (3) in a petal shaped formation. The inner contour of the cup has been formed.
so that its surface is always "washed" by hot combustion products, regardless of operating rates.

Because the refractory cup surface is heated by high velocity combustion products at their highest temperature, it becomes incandescent. Combustion is always completed within the cup. Any "hazel' seen beyond the cup is caused by incandescent products of combustion. Radiant heat from these burners can be directed accurately and travels more rapidly than convected heat from hot gases.

Figure 109: Operating principle of cup burner (Selas)

Some application examples are shown in figure 111.

Moving strips
Cup-shaped radiant burners can be used for annealing ferrous and non-ferrous metal strip, preheating for galvanizing, reflowing of electrolytically deposited tin plate and for drying inks, textiles and paper.

"In-line" arrangements
Arranged in close, circular patterns, cup-shaped radiant burners raise metal temperatures of continuously moving billets, rods, pipes and tubes at previously unobtainable speeds while maintaining optimum temperature uniformity.

**Fixtured conveyors**
Small parts in large volume are heated by conveying them past rows of cup-shaped radiant burners, with or without enclosure, placed along one or both sides of conveyor. Parts are often rotated during heating to assure uniform heating.

**Conveyorized furnaces**
Time-temperature cycles and uniformity (or non-uniformity) of heat in conveyorized furnaces, ovens, lehrs and kilns are effectively developed by strategic positioning of cup radiant burners in roof and/or wall patterns.

Figure 111: Applications for cup-shaped type radiant burners (Selas)

These small radiant burners can work on a maximum mixture pressure of 150 mbar mixture pressure. With some of the types a line arrangement can be made for heating moving webs. Some of the small radiant burners are designed to be cemented into a horizontal of vertical refractory wall or panel. The program of furnace radiant burners comprises types for applications above 1100 °C. These are of all ceramic construction. These burners can be delivered for flat and cylindrical furnace walls.

Figure 112 shows some radiant burners for open firing (non-furnace use), they represent an integral construction capable of handling a wide range of problems varying in heating intensity and geometric arrangement. Applications are such as brazing, soldering, drying, heat treating and curing.

Figure 112: Radiant cup-burners (Selas)

Figure 113 shows a line burner arrangement. These burners provide close coupling of radiant heat sources for use in "line" arrangements which are found in heating applications such as moving webs.

Figure 113: Radiant cup line burner arrangement (Selas)
Figure 114 shows cup radiant burners for mounting into vertical refractory walls or panels. These burners are designed for light furnace work (max. temperature about 950 °C).

![Figure 114: Cup radiant burners for light furnace applications (Selas)](image)

Finally there are the cup radiant burners for high temperature furnace applications (see figure 115). All parts of these burners which are exposed to high furnace temperatures are made of ceramics.

![Figure 115: Cup radiant burner for high temperature furnace application (Selas)](image)

**Burners For Closed Combustion Chambers**

Examples of closed combustion chambers are ovens and furnaces. For this type of chambers essentially sealed-in type burner nozzles also called tunnel burners are applied.

Sealed-in nozzle consists of a square or round casting with one single opening through which the mixture passes into a refractory tunnel in which is a slight taper. This is called multiple stage internal design. Burner nozzles of this type are usually applied to higher temperature furnaces where more exact control of the atmosphere is desired since these burners do not require secondary air and are supplied with a full premixed air and gas mixture. Since the metal nose of the burner is completely protected by refractory and is exposed to very little radiant heat, this type of nozzle will give long trouble-free service when properly installed. However, today for most normal furnace applications nozzle mixing burners (see chapter V) are applied. For this reason these burners are only discussed briefly here. Figure 116 shows a typical tunnel burner where flame retention is achieved by sudden enlargement of the combustion area.

![Figure 116: Section view of tunnel burner assembly (Stordy-Hauck)](image)
Figure 117 shows a sealed-in nozzle where flame retention is accomplished also by sudden enlargement of the combustion area. This construction is called multiple stage internal design.

![Figure 117: Sealed-in nozzle (Maxon)](image)

Figure 118 gives a selection graph for sealed-in type nozzles in which capacities are given in relation to supplied mixture pressures for different sizes of burners.
Figure 118: Selection graph (Maxon)

Figure 119 shows another make sealed-in nozzle.
Figure 119: Sealed-in nozzle (Eclipse)

Figure 120 shows an example system of a sealed-in burner installation with modulating control. The motorized butterfly valve at the blower outlet gives modulating control of the burners.

Figure 120: Burner installation with sealed nozzles
IV COMBUSTION FANS AND CONTROL VALVES

(omitted, 10 pp {106-116})
CHAPTER V  NOZZLE MIXING BURNERS

All burners described in chapter III are supplied with a premixed gas/air mixture produced by a mixer. These mixers where discussed in chapter 11. In this chapter we will discuss the large group of nozzle mixing burners. It will not be possible to discuss all the available burners on the market but we will try to describe the main types.

As stated before, nozzle mixing burners are types of burners in which the fuel and air are not mixed until just as they leave the burner part, after which mixing is usually very rapid. In this type of burner the flame can not flash back. The fuel gas and combustion air are thus kept separate within the burner itself. The nozzle orifices are designed so as to provide rapid mixing of the gases as they leave. Nozzle mixing burners can be divided in three groups.

A  burners for oven and furnace applications;
B  burners for industrial air heating applications;
C  burners developed for single applications such as immersion tubes or incinerators etc.

The groups A and B will be discussed in this chapter, the group C burners will be discussed in chapter VII.

A  Burners for ovens and furnaces

All the nozzle mixing burners for oven and furnace applications are "one flame" or also called forward flame burners.
Since fuel gas and combustion air are kept separate till after the air and gas spuds, flashback is not possible. For this reason there is no need for a limited minimum fuel gas and/or combustion air pressure inside the burner as had been described for premix burners. Due to this feature nozzle mixing burners can in general have a very large turn-down ratio of maximum about 40:1. The gas and air pressure at the burner spuds should of course be higher than the combustion chamber pressure.

Figure 134 shows a typical nozzle mixing burner.

In this burner flame retention and stabilization is achieved by sudden enlargement of the inside burner block, also called multiple stage internal design.
The combustion air and fuel gas should be supplied to the nozzle mixing burner in the right proportion over the total turn-down ratio for which a proportioning air/gas valve system is needed.
Most nozzle mixing burners supply gas through the center and combustion air around this center. This construction gives a stable flame. Figure 135 shows a typical selection table for this type of burner.

![Selection table for burner of figure 134 (Maxon)](image)

From the selection table can be seen that a maximum of 61.5 mbar (615 mm WC) combustion air pressure is needed for the burner to reach maximum capacity.

![Nozzle mixing burner (Eclipse)](image)

Figure 136 shows another nozzle mixing burner. This burner can be fed with preheated combustion air (till 300 °C). On the cross sectional view the operating principle of the burner can be seen. Combustion air and fuel gas supply are controlled with air and gas valves similar to the mentioned micro ratio valve systems (see figure 137).
Figure 137: Multiple burner installation controlled by a micro ratio

Also an air/gas proportioning system can be applied such as shown in figure 138.

Figure 138: Single burner installation with proportioning control (Eclipse)

This type of burner will need an air pressure on the burner of 50 mbar. Maximum turn-down ratio of this burner is 15:1. A modern design of this burner (fig 139) is capable of working with 500% excess air. This burner is designed for applications such as kiln preheating etc. and where oxidizing conditions are desired.¹²⁰

Figure 139 shows a modern nozzle mixing burner. The burner is designed for applications on industrial furnaces, ovens and kilns, for firing close to the theoretical air gas ratio, with reducing atmosphere or with excess air. More than 500% excess air can be fired with this burner and up to 40% excess gas. Turn down ratio of these burners is high. Maximum capacities of these burners are reached with 107 mbar combustion air pressure.
Whereas above described burner supplies gas through the center and air cross-wise around the center, the following burner feeds air through the center.

Since the air flow rate is much greater than the gas flow rate, it is possible to design this center air feed type nozzle mixing burner so that the air will partially entrain the gas and so requiring very low gas supply pressures. The center air feed type concentrates the air in a single jet so as to produce a flame of high forward velocity that can provide deep heat penetration into a furnace.\cite{121}

The above shown burner which feeds air through the center has a metal jacket around the tile to support the tile when the burner is mounted in a thin metal wall such as an oven or air heater. These metal jackets are called in catalogues seal and support housings. In conventional furnaces, the refractory walls provide support for the tile. A metal seal and support housing should never be used in a refractory wall because it will overheat, oxidize, melt and destroy the tile and surrounding refractory. The next figure shows pictures of a nozzle mixing burner without and with seal and support housing.
Large capacity burner

Above figure shows a typical modern large capacity burner (800-17500 kW). This burner can be fed with all types of fuel gases and fuel oils. The combustion air pressure for this burner can be selected between just 5 and 40 mbar by accommodating the burner baffle. The burner has a very high capacity turn-down ratio at 40 mbar air pressure. Preheated combustion air can be supplied to this burner up to a temperature of 650 °C.

Flat flame burners
In some furnace applications a deep penetration of the flame and hot combustion gases is not desired. For these applications nozzle mixing flat flame burners have been designed as shown in the following figure 143.

Figure 143: Flat flame burner (Maxon)

(A few premix burners are also designed to produce similar flame shapes.)

The shown flat flame burner actually heats its own refractory tile and the refractory surface of the surrounding furnace wall or roof by convection from the high velocity combustion gases thrown side ways from the burner. These hot refractory surfaces then radiate heat to the furnace load. In the two figures below some designs are shown.

Figure 144: Flat flame burner (Eclipse)       Figure 145: Flat flame burner (Stordy-Hauck)

These burners all provide a radial flame pattern which eliminates flame impingement and reduces hot-spotting and permits larger loadings of furnaces. Figure 146 shows the temperature distribution pattern measured in the open.
Figure 146: Temperature pattern (°F) of a flat flame burner (Maxon)

Maximum **turn-down ratio** of one of these burners is 30:1 and 15:1 for the other. They can burn with 20% excess fuel and up to 200% excess air.

The flat flame is produced by the spinning action of the supplied combustion air and in some makes the fuel gas and most important by the internal shape of the burner block. The influence of the shape of the burner block is shown in figure 147.

Figure 147

Some types are designed to be fed with preheated combustion air. They are all designed to give maximum capacities at 70 mbar combustion air pressure on the burner.

**High and medium velocity burners**

In some furnaces a good temperature distribution is needed with improved convection on the product. This can be accomplished by high velocity nozzle mixing burners as shown below.

Figure 148: High velocity burners (Eclipse)
Due to better heat transfer from the fast moving combustion gases a lower temperature can be maintained in the furnace. In all cases the costs of extra electrical energy needed for extra combustion air pressure will not match the energy savings due to the better heat transfer. The intense stream of combustion gases at a discharge velocity of about 160 m/s improves the circulation of the hot oven atmosphere causing improvement of heat penetration and temperature uniformity throughout the load.

Gas savings of 20-40% are achieved with high velocity burners. Many of the high velocity burner manufacturers are able to deliver burners for either stoichiometric combustion or excess air firing up to 2300% and also 40% excess fuel at maximum capacity. This makes the application of high velocity burners possible for all sorts of furnace atmospheres and temperatures.

There are two types of high velocity burners on the market:

- the high velocity type with exit velocities up to 210 m/s. For these velocities combustion air pressures are needed up to 80 mbar;
- the medium velocity type with exit velocities up to about 100 m/s.

Some of the makes are able to deliver the burners in special configurations for preheated combustion air up to about 350 °C. One manufacturer reported a high velocity burner that could be fed with 500 °C combustion air.

Figure 149 shows two high velocity burners with silicon carbide combustion tube and conventional combustion block.

The burner equipped with a silicon carbide combustion chamber is extremely suitable for application in furnaces with ceramic fibre walls. Also the shown burner can work with up to 900% excess air and up to 20% excess gas. As a result these burners are suitable for a wide range of industrial applications as tunnel kilns intermittent furnaces in the ceramic industry and metallurgical heat treatment furnaces.

Figure 151 shows a typical selection table for the described (one out of a series) high velocity burner.

Figure 150 shows another modern type high velocity burner.
Figure 150: High and medium velocity burners (Stordy)
Figure 151: Selection table and graph for high velocity burner (Elipse)

Figure 152 Shows a graph from which practical hot gas temperatures can be read at different percentages of excess air.
Figure 152

Figure 153 is showing other modern high and medium velocity burners. These burners are also capable of firing with 2200 excess air and 40% excess gas with 40:1 turndown ratio involving the capability to provide these burners with maximum 400 °C preheated air.

Figure 153: High velocity burner (Maxon)

Radiant tube burners

In chapter III the radiant tube burners were discussed as a part of infrared heating systems for processes. In this chapter we will more concentrated on the burner itself being a nozzle mixing type burner and the integration of the burner with the radiant tube.

Radiant tubes are frequently required to provide furnace temperatures of about 950 °C to about 1050 °C and for the alloy steel which is usually applied it is important that no part of the tube comes much above the mean tube temperature. This means that uniformity of tube temperature is very important.

There are some basic approaches in the design to obtain temperature uniformity.

- By controlling the combustion and heat release pattern along the tube, usually by using a long largely laminar diffusion flame which gives a slow progressive heat release pattern.
- By using jet-driven recirculation to re-entrain flue gases so that the high temperature flame gases are diluted by large amounts of gases at a temperature near that of the furnace.

A burner of the first category is shown in figure 154.
Figure 154: Burner assembly of a radiant tube burner (Stordy-Hauck)

Above burner is designed to produce a long flame. This burner is provided with flame length control so that the length of the flame can be adjusted to fit the tube. In this burner the major portion of the secondary or combustion air is introduced around the outside of the flame retention nozzle. This diverted air flow enables the prolongation of combustion over a greater distance to get the best heat distribution.

Figure 155 shows another burner for radiant tubes. In this burner the ratio between the primary and secondary air can be adjusted to provide control over the flame length as also described above.

Figure 155: Radiant tube burner (Eclipse)

These types of burners are also ideal as immersion burners on high temperature applications, such as salt baths and soft metal melting. The shown burners are available for mounting in 411 to 811 tubes. Capacity range is about 140 to 500 kW.

Figure 156: U-tube and straight radiant tube
Figure 156 shows two popular tube arrangements. The bend of the U-tube can assist in mixing but is also likely to give rise to hot spots. Temperature variation along the tube may be up to 300 °C. The straight tube might show hot spots at the tube end.

Better temperature uniformity is in general achieved if the combustion products are recirculated (second category) more than once through the radiant tube. High levels of the recirculation are achieved using high exit velocity burners. Figure 157 shows a radiant tube with a high velocity burner. The burner here is a recuperative burner working in accordance to the burner described near figure 265 (Rekumat burner). Within the alloy tube a segmented ceramic inner tube is inserted (see figure 157). This ceramic tube is provided with holes for selective supply of combustion gases between the inner and outer tube. Another purpose of the inner tube is to prevent direct flame impingement on the outer tube thus preventing hot spots. A very recent development comprises the use of described high velocity burner in a so called P. tube or double P. tube without inner tube (see figure 158).

Figure 157: Radiant tube burner with ceramic inner tube and recuperator (Thermtec-Rekumat)

Figure 158: Mounting of high velocity recuperative burner in P. and double P. tube (Thermtec-Rekumat)

Due to the high impulse giving a high rate of recirculation the inner tube can be emitted.

Most modern installations today are equipped with some sort of heat recuperative system as shown above where the heat exchanger is integrated with the burner. Another system is to pass the leaving exhaust gases through a separate heat exchanger at the end of the tube (see figure 159).
Delayed mixing gas burners or luminous flame burners

In some operations, direct flame radiation over a large area is desirable. This is frequently the case in wide or extremely long furnaces where a poor heat distribution (that is, hot spots and cold spots) would be obtained from the ordinary clear flame combustion. The physical limitations of arranging clear flame burners make it impossible to raise all of the internal surfaces of such furnaces to a uniform temperature because it is not possible to spread the combustion over a large space. Luminous flames have a considerable length and they can fill a large volume of combustion space with flames of approximately equal temperatures.

A greater part of the available refractory area may therefore be utilized for re-radiation to the work. This permits a more effective utilization of the hearth area because of the existence of a uniform temperature head throughout the combustion space. Long flames can be produced only if the rate of mixing of the gas and air is very low so that the two fluids travel a considerable distance from the burner before mixing and burning. Strong heating of the gas in the absence of air breaks down (cracks) some of the gaseous hydrocarbons into free carbon and hydrogen. It is these carbon particles which become luminous and emit radiant energy. The higher the concentration of carbon particles, the greater is the amount of radiated energy.
Both long and luminous flames are produced by the same mechanical action at the burner. In fact, it is difficult to produce one without the other. This is accomplished by injecting low velocity, non-turbulent, parallel and adjacent air and gas streams into the combustion space. This provides a low mixing rate as needed for a long flame because mixing occurs only at the interface between the parallel gas and air streams. If the burner is arranged so as to inject a central core of gas completely surrounded by an annular air stream, the combustion which occurs at the air/gas interface will radiate heat to the gas stream, causing it to crack and produce luminous carbon particles.

B Burners for air heating applications

Nozzle mixing burners for air heating applications form a totally separate group of burners. In the part of this information about premixing burners we already discussed a number of premix line burners for air heating. This part will mainly discuss nozzle mixing line burners for air heating although there are also some important forward flame burners for air heating which will be discussed. These applications are called direct fired air heating systems. A direct fired air heating system is a system in which the combustion gases are directly mixed with the air to be heated, so there is no exhaust loss. All the heat developed during combustion is thus absorbed by the process air.

Direct fired air heating is possible with natural gas because natural gas, not containing sulphur, only produces during combustion CO2 and H2O and at ppm level some CO and NOx. In all drying processes which allow direct contact between the product and combustion gases from natural gas, direct fired air heaters can be applied. Compared with the indirect air heaters, such as steam heaters, this means a gas saving of about 15% or more.

By varying the load on the burner any desired temperature can easily and quickly be reached. A major advantage is that it is possible to obtain considerably higher temperatures than with indirect air heater systems. In addition, the system has a wide operating range. Because in modern direct heating systems refractory linings are not needed, investment and maintenance costs are lower than heat storage. When directly heated air is used for drying foodstuffs low NOx burners should be applied. NOx contained in directly heated air can react with amines associated with the foodstuff proteins to produce impurities which could constitute a serious health hazard when the food is assimilated. A NOx concentration of the order of 50 ppb in gases used for this purpose is seen as the permissible maximum. This means that the burner may produce no more than 1,5 mg NOx per MJ heat input.

At present burners are available which are able to meet this requirement.

Nozzle mixing burners for direct air heating can be classified roughly as follows:

- line burners without combustion air supply;
- line burners with partial combustion air supply;
- line burners with complete combustion air supply;
- line burners with stoichiometric combustion air supply;
- forward flame burners for air heating;
- line burners for incinerators;
- special burner arrangement for air heating.

Line burners without combustion air supply

Many of the industrial gas burner manufacturers have developed line burners for direct fresh air heating only. These designs make it possible to operate the burner without combustion air supply by a blower. The principle of a line burner mounted in an air stream is shown by the cross sectional view shown in the figure below.
These burners are often named make up air line burner. The shown burner is the AIRFLO type of Maxon Corp. but also other industrial burner manufacturers are producing a similar type make up air line burner. As stated the burner will be fed with natural gas (propane is also possible) under a pressure of about 20 mbar. The supplied gas is then distributed through the manifold and flows then through the burner holes into the area between the perforated mixing plates (see figure 162).

As can be seen in above figure a profile plate is mounted inside the duct which is situated at the end of the burner profile plates. Due to this the air to be heated passing the burner and the profile plate will get a higher velocity (max. about 20 m/s) in the slots giving a pressure drop over the profile plates. Due to this pressure drop, air for combustion will flow through the holes in the burner mixing plates. Between the profile plates mixing takes place of the supplied gas and air. Thus all the combustion air is taken from the air stream of the air being heated. The total amount of air flowing through the mixing plates is about 60% more than is needed for combustion (n=1.6) at maximum capacity.

The air flowing through the mixing plates can best be compared with impulse jets entraining the supplied gas giving an intensive swirl of air and gas. At minimum capacity all the supplied gas will be mixed with the air supplied through the first two rows of small holes in the mixing plates giving a small flame in the throat of the burner as shown in the next figures.
The air flowing through the other and bigger holes in the mixing plates is not used for combustion. If more gas is supplied, gradually more air flowing through the holes in the mixing plates is used for combustion. At about 50% of maximum capacity the flame pattern will be as shown in the next figure.

At maximum capacity the flame pattern will be as shown in the next figure.

The capacity of the burner is thus controlled just by adjusting the flow of gas to the burner. Turn down ratios up to 30:1 maximum can be obtained with these types of burners. At each pressure drop over the burner another amount of air will flow through the mixing plates giving another maximum capacity of the burner. For some of these types of burners the air velocity passing through the burner can be altered by 2:1 (100 to 50%) giving a capacity change of 2:1.

In general these burners are designed for heating constant volumes of air. For some types and makes the mixing plates are of a sophisticated design which provide very complete and clean combustion of the fuel over the total range of firing rates. Due to the mentioned 60% excess air a rather cool flame is maintained giving low NO, production. Also the production of CO is very low (less than 2 ppm at 50 °C temperature rise). Due to these features these burners are applied for make up air applications for supplying heated fresh air into large construction buildings etc. For many drying processes which need constant volumes of heated make up air such as spray dryers above mentioned features may also be important. Some typical characteristics of these burners are:
- Many types from rather low to very high outputs per foot of burner length are available combined with very clean combustion and high turn down ratios (see also next pages).
- The construction of these burners is very simple (no moving parts) and a combustion fan is not needed.
- The capacity of these burners can be controlled by just using a butterfly valve in the gas supply line.
- A wide variety of burner configurations (see figure 168) is available.
- The shape of the mixing plates together with the flat profile plates provide an intensive mixing of the air to be heated with the combustion products of the burner.

Make up air line burners on the market:

It will be impossible to describe and show all the burners of discussed type on the market.
The type shown in figure 167 can be delivered in capacities and other data given in the table from figure 149.

Although these burners are in principle designed for just heating fresh air with about 21% oxygen the most modern types can also heat air with lower oxygen percentages. These burners are also designed for further heating hot supply air.

Figure 167: Make up air line burner section

Figure 168: Some make up air burner sections (Maxon)
Figure 169: Capacity table of some make up air line burners (Maxon)

Figure 170 shows such a design of a developed line burner. These burners are able to work at maximum approach temperatures of about 540 °C and minimum oxygen levels of about 14%.

Figure 170: Line burner section (Maxon)

The given capacities in the above shown tables are all based on a pressure drop over the burner of 1.5 mbar. At higher pressure drops higher capacities are obtained. The given maximum capacities in above table (figure 171) are based on the maximum approach temperatures given in the table. At lower supply temperatures capacities are reached which are a little higher. The first value given is based on the maximum given supply temperatures at an oxygen percentage of 20.8 (normal air). The second value is based on the same maximum supply temperature and 14% oxygen.

Figure 171: Capacity table of some line burners (Maxon)
Figure 172 shows another make up air line burner. This burner has a capacity per 30 cm of burner (1 foot) of 170 kW at 1.5 mbar pressure drop. The maximum turn down ratio is 30:1. The shown burner is designed for fresh air heating only.

Figure 172: Make up air line burner (Eclipse)

Figure 173 gives a picture of another make up air line burner with similar capacities.

Figure 173: Make up air line burner (Stordy)

**Line burners with partial combustion air supply**

The operating principle of these burners is similar to the line burners described above with the difference that some combustion air is premixed with the gas and supplied to the burner manifold. In most cases not more than 30% of the needed combustion air is premixed with the fuel gas. Most commonly blower mixers as shown in figure 174 are applied to supply the mixture of 30% combustion air with fuel gas.

Figure 174: Blower mixer (Maxon)

This premix combustion air makes the line burner to a certain extent, independent of the oxygen content of the air stream which passes to be heated the burner. Due to this these types of burners can be applied in recirculating air streams having less than 20.3% oxygen (but more than 16%).
For this reason these types of burners are generally applied in dryers to heat recirculating air flows. Figure 175 gives a picture of such a line burner. From the picture can be seen that the burner body is larger in comparison with the make up air line burners. This is needed because at 30% combustion air premixing, on every m' of gas about 3 m$^3$ of air should be transported with the gas. The shown burner has a capacity of about 170 kW per foot of burner.

![Figure 175: Line burner for partial combustion air supply (Maxon)](image)

**Line burner with complete combustion air supply**

These burners are in principle the same as the types discussed under line burners without combustion air supply. The difference is that these burners are in general supplied with combustion air by a fan. The next figure explains the burner principle.

![Figure 176: Line burner with complete combustion air supply (Eclipse)](image)

A combustion fan supplies the combustion air which is transported through the perforated plate 2 to produce a uniform air flow to the total length of the line burner. The line burner is closed in (surrounded or enveloped) by the air supply duct 3 due to which all the combustion air must flow through the holes in the burner plates. The supplied combustion air mixes between the burner plate with the supplied gas as described under line burners without combustion air supply. Capacity of these burners is controlled by a butterfly valve in the gas supply line. The combustion air is not controlled and is maximal at all firing rates. It will be clear that these burners are less independent from passing air velocities than the burners described before, however at least 7.5 m/s passing air velocity is recommended to get proper mixing. Since no profile plating is needed there will be less pressure drop over the burner and less electricity consumption of the transport fan. However also less rapid mixing might be expected.
The combustion fan can be situated inside or outside of the air transport duct as shown in the next figure.

Figure 177: Combustion air fan situations
Figure a: Internal mounting fan and burner are used in case fresh outside air must be heated. Fresh air enters also the combustion fan and the combustion air pressure will change with the air pressure in the duct.
Figure c: External mounting fan with internal burner is used for recirculating air heating applications where hot or warm air must be heated with sometimes lower oxygen percentages. In this case the fan static pressure should be the duct static pressure plus the pressure needed for the burner.
Figure d: In this case also outside combustion air is supplied to the burner. This system can be applied if the pressure inside the duct is sufficiently negative to draw in enough air for combustion. The system can also be applied if combustion air is supplied through a control supply duct.
Figure e: This arrangement is similar to the systems discussed under burners without combustion air supply.

In above figures a-e the burner was mounted inside the duct. These types of burners can also be flange mounted or mounted externally as shown in the next figures.

Figure 178: Burner mounted outside of duct (Stordy)
Above photograph shows a typical line burner as just described under figure 177a. Some typical
characteristics of these burners are:
- rather high capacity per 30 cm of burner length (1 foot) being 230 kW with a maximum flame
length of about 700 mm
- average turn down ratio of these burners is 25:1;
- the capacity of these burners can be controlled by just using a butterfly valve in the gas supply
line;
- wide variety of burner configurations (as shown before) as well as capacities are available;
- no profile plates are needed. Air to be heated must pass the burner at velocities between 7 and 25
m/s;
- required combustion air supply is 340 M3 per 30 cm of burner length which is about 55% excess
air \( n = 1.55 \);
- the maximum temperature downstream of these burners should be limited to about 750 °C.

Figure 180 shows a typical nozzle mixing line burner. This burner possesses almost the same
features as described above. With this burner the combustion air supply can be based on 10%
excess at maximum firing rate.

**Line burners with stoichiometric supply of combustion air**

Modern dryers require a minimum possible make up air or replacement fresh air supply to work
fuelwise as economical as possible. For this reason it may be needed that combustion products
supply to the dryer from the burners in mass volume should be kept to a minimum. This can be
achieved by supplying just the stoichiometric combustion air amount or less. Sometimes the
oxygen for combustion can be taken from the recirculating air stream. If constant recirculating
volumes should be heated and the available oxygen percentage is not too low, some of the
described burners under "line burners without combustion air supply" can be applied. A little less
dependent of the recirculating air streams are the line burners with partial combustion air supply. Here we will briefly describe line burners with stoichiometric supply of combustion air. Figure 181 shows a line burner of this type. Combustion air is piped to the burner independent of the process air stream at an over pressure of about 36 mbar. No mixer for premixing is needed. With this burner also 25% rich (excess) gas can be fired. Maximum turn down ratio is 30:1 at a maximum capacity per section (1 foot) of 300 kW.

Figure 182 shows a possible control system using a cross-connected proportionator valve (D). As air flow is varied by the firing rate controller, changes in air pressure are transmitted to the proportionator valve which varies gas flow accordingly. These burners can, if required for extra fuel saving, be fed with preheated combustion air (max. 230 °C).

Figure 181: Front view of a stoichiometric fed line burner (Eclipse)

Figure 182: Control system (Eclipse)

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Firing rate controller</td>
</tr>
<tr>
<td>B</td>
<td>Low fire adjusting valve</td>
</tr>
<tr>
<td>c</td>
<td>Check valve</td>
</tr>
<tr>
<td>D</td>
<td>Adjustable bias proportionator</td>
</tr>
<tr>
<td>E</td>
<td>Gas adjusting valve</td>
</tr>
<tr>
<td>F</td>
<td>Pilot solenoid</td>
</tr>
<tr>
<td>G</td>
<td>Gas pressure measuring device</td>
</tr>
<tr>
<td>H</td>
<td>Air pressure measuring device</td>
</tr>
</tbody>
</table>
The stoichiometric fed line burners are also suited for recirculating air systems in which oxygen content or total air flow must be closely regulated. It should be noted that also the described premix type line burners can be applied of near stoichiometric air supply is required. In general however premix type burners are more sensitive to process air pressure changes and have less turn down ratio.

**Forward flame burner for air heating**

Forward flame burners for air heating are often easier to install on an air duct than most of the line burners. Figure 183 gives an example of such a burner.

![Figure 183: Principle of forward flame burner for air heating (Maxon)](image)

The working principle of this nozzle mixing burner for air heating is as follows (see above figure 183 and figure 184). Air is supplied by a combustion fan and is transported tangentially through the burner cone where it is mixed with gas supplied through a ring of holes in the center of the burner. Circular flanges are provided at the inside of the cone to improve mixing. The flame is formed inside the cone and the actual burning takes place inside the burner sleeve. The burner sleeve is cooled at the inside with a thin layer or film of fresh air. Turn down ratio of these types of burners is maximum 40:1. The flame of these burners is very stable. Air velocities up to 10 m/s.
Perpendicular to the flame give no problems. Air and gas are controlled together. At maximum capacity there is an excess air supply of about 25% ($n = 1.25$) while at minimum capacity excess air is about 10013% ($n = 11$). These types of burners can be applied for many drying processes where recirculating air must be heated. The combustion air fan can be delivered as an integral part of the burner (see figure 184) or the burner can be delivered without fan (see above figure 183). In the last case the burner is connected with an air supply duct with a central blower. Some features of this burner are:

- very good flame stability and large turn down ratio;
- in practice these burners prove to be not very sensitive to changing back pressure;
- these burners are very simple to install.

Another design of a forward flame nozzle mixing gas burner for use in process air heating applications such as ovens and dryers is shown in figure 185. In comparison with the above described burner this burner is able to work with less excess air at maximum and low firing rates (10% at max. capacity and 20% at minimum capacity).
Recent developments indicate that forward flame burners for air heating will be available with almost stoichiometric combustion air supply over the total turn down ratio as has been reported by Maxon.

**Line burners for incinerators**

Many industrial processes use various types of organic solvents in operations such as paint baking and drying, enamelling, lithographing, printing, curing, setting and polymerizing. Control of these organic solvent emissions is becoming mandatory in many metropolitan areas with the enactment of air pollution statutes and establishment of enforcing agencies. In all above-mentioned processes the hydrocarbon pollutant level is below the lower explosion limit (max. 40% of the lower explosion limit L.E.L.).

For oxidation or incineration of these hydrocarbons, which will take place if all the polluted exhaust gases are heated to about 750 °C, special line burners were designed (the subject will be discussed in more detail later). The line burner types shown in figure 186 and figure 187 are widely applied by various manufacturers.

Figure 186: Line burner section for incineration
These burners are all natural gas (or propane) burners with combustion air taken from the fume stream. They are able to work on oxygen levels in the supplied fume stream as low as 16%. The next figure shows the operation of these distributed line burners.

The profile plates are used to block most of the area between burner and wall. The opening between profile plate and burner edge is based on 4 mbar AP of the exhaust gases during operation. About 50% of the exhaust gases will pass the burner (between profile plate and burner edge) and the other 50% will flow through the holes in the burner plates into the V-shaped combustion area to provide oxygen for combustion. Incineration will further be discussed in a separate chapter. For the German market circular or cone type or almost circular burners for incineration were developed as is shown in figure 189.
Special burner arrangement for air heating

A special burner arrangement for air heating which should be mentioned is shown in figure 190. In this type of burner hot combustion gases from a nozzle mixing burner are supplied in a heat resistant distribution pipe. Out of this distribution pipe the hot combustion products are injected in the process air stream (18.. 20 mbar excess pressure in the pipe) The burner, which is on the outside of the duct, is a nozzle mixing burner with 20:1 turn down ratio. To prevent overheating of the distribution pipe the burner is supplied with 50 to 100% excess air over the total turn down ratio. With this type of burner very even air heating can be obtained. This might be necessary in some drying processes where heating temperatures are needed within very narrow margins.
VI BURNER RELATED SUBJECTS

In this chapter the following subjects will be discussed:

- calculation method for air heating applications;
- burner piping;
- the use of ceramic fibers for the thermal insulation of gas fired furnaces;
- burner safeguarding;
- gas trains.

Calculations in air heating when applying fuel gas for direct heating

In this part of the book we will describe how needed capacities can be calculated when air is directly heated with natural gas.

Direct heating is a system in which the combustion gases are mixed with the air to be heated.

Make-up air heating

Make-up air heating is a system where fresh outside air is heated to a temperature needed for the process such as flash and spray dryers.

Let us assume that 50 000 kg of dry air per hour must be heated from 20 °C to 220 °C for a spray dryer. The inlet air has a relative humidity of 70% which is 10 grams of water per kg of dry air (see Mollier Diagram in the appendix).

To calculate the capacity the next general formula is applied:

\[ Q = M \times C_{\text{pm}} \times \Delta T \]  

in which

- \( Q \) is the capacity in kW
- \( M \) is the mass flow rate to be heated in kg/s
- \( \Delta T \) is the temperature rise in K
- \( C_{\text{pm}} \) is the mean specific heat value in kJ/kg K.

<table>
<thead>
<tr>
<th>T/°C</th>
<th>lucht</th>
<th>water</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1,01</td>
<td>1,79</td>
</tr>
<tr>
<td>100</td>
<td>1,01</td>
<td>1,8</td>
</tr>
<tr>
<td>200</td>
<td>1,01</td>
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<td>300</td>
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<td>1,96</td>
</tr>
<tr>
<td>800</td>
<td>1,07</td>
<td>2</td>
</tr>
</tbody>
</table>

Figure 190: cp air, water in kJ/kgK (1 m³₀ = 1 m³ at 0 °C and 1,01325 bar = 1,3 kg air).

In the table of figure 191 the average or mean specific heat values for dry air and water vapor are given per kg and per m³₀ of dry air. {155}

Many practical calculations only use the Cpm of air to calculate the needed capacity.
For our example the calculation of the needed heat will then be:

\[
\frac{50000}{3600} \times (220 - 20) \times 1.01 = 2805 \text{ kW} \tag{1a}
\]

In this calculation the following is not taken into account:
- The water vapor carried with the dry air
- Combustion gases from a burner

If we also heat 10% (mass) water vapor carried with the dry air the capacity will be:

\[
\frac{50000}{3600} \times (220 - 20) \times (1.01 + 0.01 \times 1.83) = 2856 \text{ kW} \tag{1b}
\]

For fresh air heating line burners without combustion air supply are used. This means that the oxygen for combustion is taken from the air to be heated (see chapter III).

Figure 192 gives a scheme of such an installation.

![Diagram of line burner](image)

The gas consumption will be:

\[
\frac{Q}{\text{net heating value (m}^3/\text{s} \times 3600 \text{ m}^3/\text{h)}} \tag{2}
\]

\[
2856 \times 3600 / 35,88 = 286 \text{ m}^3/\text{h} \tag{2a}
\]

In the calculation of the capacity the water produced by combustion does not have to be taken into account, because that is part of the net heating value.

Methane produces 1.9346 kg $\text{H}_2\text{O}/\text{m}^3_0$ gas. The amount of water added to the air stream is then:

\[
1.9346 \times 286 = 553 \text{ kg/h}
\]

The gas mass flow supplied is (mass methane 0.7175 kg/\text{m}^3): 286 x 0.7175 = 205 kg/h.

Total mass flow after burner is: 50 000 + 205 = 50 205 kg/h

Total water flow after burner is: 50 000 x 0.01 + 553 = 1053 kg/h

Total amount of dry air is: 50 205 - 1053 = 49 152 kg/h
Amount of water per kg dry air is: 1 053 000 / 49 152 = 21.42 g H$_2$O/kg dry air.\textsuperscript{1}
Heating of recirculating air flows

In many dryer types such as continuous sheet or web dryers, tunnel dryers etc. recirculating air streams having a high moisture content must be heated. For direct heating of recirculating air flows in most cases line burners are applied with complete combustion air supply. Figure 193 gives a scheme of such an installation.

![Diagram of recirculating air heating system in a continuous dryer](image)

Let us assume that to the plenum and nozzle system 10000 kg of 180 °C air at a absolute humidity of 70 g/ kg dry air should be delivered. The recirculating air has a temperature of 150 °C and an absolute humidity of 90 g/ kg dry air. The supplied fresh air is 20 °C with 10 g water/ kg dry air.

The calculation has normally the following procedure:

First the water balance is made.
Water content air out = water content recirculating air + water content fresh air
\[10000 \times 70 = 90A + 10B + 10C\]
A = recirculating air mass flow
B = fresh air mass flow
C = combustion air mass flow

C is not known at this stage because the needed burner capacity is not yet known. To solve this the installation is simplified for this purpose as shown in the scheme (Figure 194):
The water balance is now:
10000 x 70 = 90A + 10B.
B = 2500 kg/h fresh air
A = 7500 kg/h recirculated air

Through the combustion gases also water will be added. With formula [3] we can calculate that as follows:
water added = 0.046 x 30 x (1 + 90/100 x 0.23) x (1 + 150/200 x 0.05)
= 173 g H$_2$O/kg dry air [160]

This is a very small amount. In practice the supply temperature is chosen about 3% higher to obtain a little extra water pick-up and a little more fresh air should be taken in.

The heat balance can now be made.
Burner capacity = heat to dryer - recirculated heat - heat in fresh air
= 10000 x 180 x (1.01 + 0.07 x 1.83)
- 2500 x 20(1.01 + 0.01 x 1.8)
- 7500 x 150(1.01 + 0.09 x 1.83)
= 2 048 580 - 51 400 - 1 321 537 = 675 643 kJ/h
= 188 kW (+ 3% = 194 kW)
Methane consumption = 675 643 / 35.88 = 18.83 m$^3$/h.

Combustion air needed (9,565 m$^3$/m$^3$ methane)=18,83 x 9,565 = 180 m$^3$/h.
Most of these burners are working on 60% excess air, which means that
1.6 x 194 = 310 m$^3$/h = 310 x 1.293 = 403 kg/h dry air
will be supplied to the burner.

The fresh air supply will be 2500 - 403 = 2100 kg/h.
Note that the gas mass flow, which is only 18.43 x 0.7175 = 13.5 kg/h, has been neglected. Due to all the points mentioned above the fresh air supply will be about 2000 kg/h.
Burner piping

In this part a simplified selection of air, gas and mixture piping size is given. Further will be given some piping design suggestions.

Air, gas and mixture piping systems should be sized to deliver flow at a uniform pressure distribution and without excessive pressure losses in transit.

Two factors cause air pressure loss and consequent pressure variations:

1 friction in piping and bends;
2 velocity pressure losses due to changes in direction.

In combustion work piping runs are usually short (under 15 m), but often have many bends. By assuming that all velocity pressure is lost or dissipated at each change of direction and by using a pipe size to give a very low velocity pressure, other losses can be disregarded. In general, a velocity pressure of 0.7 to 1.3 mbar satisfies this need. This is equivalent to air velocities of about 11 to 14 m/s. For other gases, this velocity is inversely proportional to their gravities: consequently, higher velocities can be tolerated with natural gas, but propane and butane piping should be sized for lower velocities than air.

The velocity pressure can be calculated with the next equation:

\[ VP = 0.5 \times \text{rho} \times v^2 \]

In this equation \( VP \) is the velocity pressure in Pa (Pascal) (100 Pa = 1 mbar), \( \text{rho} \) is the specific gravity of the gas in kg/M3 and \( v \) is the velocity of the gas in the pipe in m/s.

Example: Air at a temperature of 20 °C has a specific gravity of 1.2 kg/M3. Given is also the allowable velocity pressure which is 1.3 mbar.
Solution: \( 130 = 0.5 \times 1.2 \times v^2 \) --> \( v = 14.7 \) m/s.

For sizing branch piping the equal area method should be applied. This method is based on maintaining constant total cross-sectional area in all portions of a piping system, regardless of the number of branches in each portion. In the sketch of figure 195 the equal area method requires that: Area of \( X \) = 2 times area of \( Y \) = 6 times area of \( Z \). Very often the velocity in \( Y \) is selected lower than the velocity in \( Z \).

The advantage of this method is that once the size of the smallest branch has been determined, via velocity pressures or any other valid method, the remainder of the piping system can be correctly sized without any additional calculations. Remember, however, that if the calculation of the smallest branches is in error, the entire system will be incorrectly sized.

To use the table below, figure 196, read across from the pipe size of the smallest branch in the manifold (\( Z \) in the sketch at left) and down from the number of these branches. At the
intersection, find the recommended size pipe to feed these branches. For example, if Z is 3/4”, Y should be 1-1/4” and X should be 2” pipe.

![Table showing recommended pipe sizes](image1)

Figure 196

The figure 197 presents some general manifold design suggestions.

![Diagram showing manifold design suggestions](image2)

Figure 197: Manifold design suggestions [163]

It is extremely important that the piping from the control valve or mixing tube to the burner is large enough to ensure a low velocity of the gas or gas/air mixture in the piping. If the velocity is too high to the burner, the performance of the system can be seriously impaired. Particularly with multiple burner systems or line burners with multiple inlets extreme care should be given to the selection of pipe size and length of the manifold piping. In case there are two or more burners on each side of an oven, the length of pipe on each side should be the same, so that the pressure in the two lines can equalize.
The pipe length between any manifold take-off or elbow and burner inlet A (fig. 199) should be at least $i$ diameters of the nipple used or $2.1/2$ times the main manifold pipe diameter, whichever is larger. ($4 X < A > 2.1/2 Y$).

A take-off from a manifold should be straight and not in stream as shown in figure 200. Also the take-off should be welded on the manifold in such a way that the smaller pipe does not stick into the main manifold (saddle weld), thus avoiding turbulence at the take-off point (see figure 200). The manifold should continue at least 2 pipe diameters beyond the last take-off (see figure 200).

When a large line burner is installed and more than one manifold is necessary it should be considered to use a separate control valve in each manifold which will give more flexibility in monitoring the burner (see figure 201). This is only applicable to air or gas piping. No valves or other restrictions should ever be installed in manifolds carrying gas / air mixtures.
Some further design suggestions

Do never install valves, cocks, orifices or any other obstructions in air/gas mixture piping.

Piping entering a nozzle must be the same size as that nozzle. Piping from a mixer must be the same size as that mixer discharge flange and/or equivalent in transverse area to the combined nozzle feeds as described above.

Air lines may be of almost any type of pipe, tubing or duct material if it is clean, airtight and strong enough for the anticipated pressure and temperature. Workmen often walk on horizontal air pipes, so they may need greater structural strength than dictated by the flowing fluid. Piping must have its own support brackets to avoid strain on burners, blowers and accessories.

Unions, flanges couplings should be installed wherever necessary to allow easy removal of burners, regulators, valves or accessories for cleaning, maintenance and inspection.

Suggestions on use of flexible hose

Excessive maintenance on burner blocks and castings is frequently the result of external stresses and strains transmitted to the burner through the piping. On large installations it might be well to consider the use of flexible piping connectors which can provide "give," and "take" in both length and alignment. Installation of such connectors at certain key spots in the air or gas manifolding can prevent damage to the burners from uneven thermal expansion. They may also be used near blower outlet connections to absorb vibration.

The use of a monolithic seal of castable refractory around each burner will prevent shearing of the block because of unequal expansion of the refractory and the furnace shell, IF the bolts are not made up too tightly. But there is still the possibility at times of damage because of the lateral expansion of the long piping manifolds. This can be forestalled by the installation of flexible connectors in the take-offs to individual nozzles or burners as illustrated at below (see figure 202).

The provision of flexibility is secured by the use of a length of corrugated metal of the same inside diameter at the standard pipe size of the line in which it is to be mounted. To the length of corrugated metal is brazed or welded a pair of threaded pipe nipples, two welding nipples or two companion flanges, depending upon your choice for ease of installation.
These three variations are shown below:

![Diagram of variations](image)

**Figure 203**

Some further suggestions are:

Don't compress a flexible connector to make it fit! So install it at exact normal free length as supplied. If connector is too long, shorten piping.
Also don't stretch a connector to fit a gap longer than its furnished length. Don't force rotate one end of connector to match bolt holes in mating flange. Most connectors cannot withstand torque!
Don't bend a hose sharply near fittings. Anchor flexible metal hoses at the piping end, never at the equipment end. If hoses are not securely anchored, they will transmit all vibration to the piping system. Not only that it will often act like a spring and actually amplify the vibrations.

The use of ceramic fibers for the thermal insulation of gas-fired furnaces

On refractory and refractory constructions a lot of information is available. In this chapter we will give some information about ceramic fibers because new furnaces are most often designed with ceramic fiber insulation.
Ceramic fibers are being increasingly used for the thermal insulation of gas-fuelled furnaces. When new furnaces are designed or when existing plants are retrofitted, ceramic fiber lining should be evaluated for cost reasons. In numerous heat treatment applications ceramic fibers will cut fuel consumption and reduce maintenance expenses.

State of the art of ceramic fiber lining
During the course of the last fifteen years insulation materials made of ceramic fibers have made considerable progress. Ceramic fiber felts, mats, shapes (folded mats) and vacuum-formed modules are being offered. All these products have following properties in common:

-considerably lower density than that of conventional refractories setting lower requirements for the supporting structure;
-lower installed cost through faster installation;
-excellent insulation properties;
-lower heat storage and thus faster heat-up and cool-down along with lower fuel consumption.

Essential physical properties of conventional and lightweight refractories as well as ceramic fibers and the chemical characteristics of ceramic fiber materials are summarized in the table of figure 204.
The thermal mass of ceramic fiber lining is much lower than that of conventional refractories. The excellent insulating properties are mainly due to the low thermal conductivity. Since the density of a ceramic fiber is lower than the specific weight of conventional refractories, both load bearing parts and mobile components of the furnace such as bells, doors and roofs become much lighter. In addition, ceramic fiber lining can be mounted easily and installation by bonding or anchoring has become state of the art. Thermal fatigue due to the furnace temperature cycles does not pose any problem. Depending on the share of aluminium oxide (Al2O3) and silicon dioxide (SiO2) in the fiber, the maximum furnace operating temperature is between 1100 and 1400 °C. If the material consists almost exclusively of aluminium oxide, furnaces may be run at approx. 1400 to 1500 °C and the design temperature even increases to approx. 1600 °C, if the material used is pure zirconium oxide fiber. Naturally, the limitations of the material must not be overlooked. The major drawbacks are the low mechanical stability and the sensitivity to some furnace atmospheres. Since the strength of ceramic fibers is considerably lower than that of conventional refractories, design engineers must examine very carefully whether in addition to the furnace roof and perhaps the furnace walls, the furnace floor of a bogie hearth furnace for instance can also be lined by ceramic fibers. Whereas aluminium silicate, aluminium oxide and similar fiber materials can be exposed to very high temperatures, if the furnace atmosphere is of the neutral or oxidizing type, a reducing atmosphere - in particular, if associated with a high hydrogen or higher hydrocarbon level - may significantly shorten the life of a ceramic fiber lining if the temperature in the furnace is above 800 °C.

The use of ceramic fiber materials of different types for lining furnaces and other industrial heating plant fitted with different external thermal insulation systems has become state of the art. Heavy refractory bricks are increasingly only used in applications where the heavy material is needed, for instance, because of mechanical loads or high wear.
Due to its low thermal mass and its insensitivity to temperature cycling, the lightweight material is particularly suited for batch type furnaces. If gas is used as a fuel, the combination of furnace and heating system is almost ideal.

In modern construction fuel consumption can be extremely low, if both ceramic fiber lining and recuperative combustion air preheating are combined. The chemical behaviour of ceramic fiber materials causes less problems, if gas is used for firing the furnace than if liquid fuels such as fuel oil are used. On the one hand the combustion of gas will not produce any residue or cause the deposition of sulphur compounds and corrosion due to a temperature below the acid dew point will not occur. On the other hand, a high sulphur content (e.g. 1.5% sulphur in fuel oil) may be the cause of fiber corrosion.

If ceramic fiber material is used for the thermal insulation of furnaces operating with a reducing atmosphere (H2, CO, NH3 or CH4), the furnace temperature will usually have to be limited to below the fiber design temperature, since recrystallisation may occur in the fiber. Again, though, atmosphere adjustment is more accurate if gas is used for furnace fuelling rather than fuel oil increasing the life of the ceramic fiber material.

An atmosphere containing uncombusted higher hydrocarbons of the type produced by fuel oil burners operating in an on/off mode will also shorten the life of ceramic fibers. If gas is used for firing, the problem will not be encountered.

**Design with ceramic fibers**
In this part we will briefly discuss the following constructions:

- layered ceramic fiber wall construction;
- fiber wall modules;
- stack bond constructions.

Layered ceramic fiber wall construction

A typical layered construction is shown in figure 205.

![Figure 205: Layered fiber wall construction](image)

In case of a layered construction the following data are important:

- Temperature of the hot side.
- Gas velocity.
- Are there components in the furnace gases like H2, CO, NH3, CH4?

The following design decisions can then be made:

- hot face lining material can be selected;
- back-up insulation can be selected;
- number of layers can be selected;
- type of attachment system can be selected.
For the selection of the hot face material the peak operating temperature of the furnace and gas velocity are important. In general the given design temperatures from insulation material deliverers should be lowered by 50-150 °C (see also table of figure 204). All ceramic fibers exhibit some tendency to shrink above 900 °C although most hot face layers are designed to give little shrinkage above 900 °C. This means when using ceramic fiber layer above 900 °C the first back-up layers should also be able to stand the full furnace temperature.

Special care should be given to gas velocities. Some hot face layers (very often they are called blankets) can stand gas velocities, up to 20 m/s. Sometimes a hot face layer is applied for high gas velocities containing a wet organic binder.

Although the maximum allowable temperature of these layers may be somewhat lower.

For most hot face-layers a layer density of about 130 kg/m³ is recommended.

The back-up layer should be selected for maximum temperature as discussed above but also for stability against sulphuric acid condensates which may be present when firing high sulphur fuel oils.

The second back-up layer can often be selected from a cheaper material like Rock wool. The overall lining thickness and composition of an insulated furnace wall should be determined by calculation in which parameters are:

- hot face temperature;
- ambient temperature;
- thermal conductivity of materials of construction and thickness;
- outside air velocity;
- cold face temperature;
- heat loss;
- heat storage.

Corrosive fuels containing over 0,5% sulphur will release S02 and S03 gases which will attack the shell and studwelds. An aluminium or stainless steel foil vapor barrier should be installed after the first 25-50 mm layer of blanket, where the interface temperature is above the dew point of the gases (see figure 206).

Figure 206

Most suppliers are able to determine the temperatures between each of the layers. Hydrogen in a furnace atmosphere will cause an increase in thermal conductivity of the lining.
The studs and washers (see figure 207) applied for fiber wall layers are made from alloys. The recommended maximum use temperature under normal oxidizing conditions for some alloys are given in the table from figure 208. Most of the alloy studs are 6.4 x 3.2 mm rectangular cross section bar with notches in the sides which bring the cross section back to square. Studs are welded to the shell either with an automatic gun or by manual stick welding.

![Figure 207: Stud and washer](image)

<table>
<thead>
<tr>
<th>Stud and washer material</th>
<th>Recommended use</th>
<th>USA</th>
<th>Germany</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 304</td>
<td>760 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AISI 310</td>
<td>930 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inconel</td>
<td>1090 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ceramic</td>
<td>1430 °C</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The clip 38 mm round or washer with a rectangular slot in the center fits over the stud.

For furnaces operating at temperatures above the maximum recommended use temperature of alloy studs and washers, Inconel 601 studs can be applied but must be protected from the hot face temperature. Figure 209 shows a protection for stud and washer.

![Figure 209: Protected washer](image)

For temperatures up to 1150 °C very often a ceramic cuplock is used (see fig 210). Thjis cuplock is similar in principle to the alloy washer described above and works on the same rectangular slot. The difference is that the end of the stud is buried inside the shank of the cuplock and is therefore protected.
For higher temperature applications particularly on roofs, it may be beneficial to install a ceramic bearing ring between the cuplock and the hot face material as shown in figure 211. The core of the ceramic cuplock must be filled with a moldable.

Proper anchor or stud spacing is essential for a successful fiber wall installation. Stud patterns are determined by the width of the blanket being used on the hot face layer and the operating temperature of the furnace. Most blankets are usually installed vertically on sidewalls. Figure 212 illustrates a proper stud pattern.

Corners
Wall to wall or wall to roof corners require the same staggering techniques as discussed. Below 980 °F very often the construction of figure 213 is applied. For higher temperatures the lapped join or batten strip construction with several lapped joints in backup layers is used, see figure 214.
Burner blocks
Just about every type of gas or oil burner can be used with fiber wall lining, including flat flame types. With conventional refractory construction the brick or castable sidewalls usually provide the support for the burner block. A fiber wall will not support the weight of a burner block. Moreover the fiber wall is much thinner than a conventional refractory lining. For this reason a shell (burner support housing) to support the burner block must be attached to the furnace shell (see figure 215). A layer of fiberfrak blanket between the casing and block will cut down on heat transfer from the block to the can and allow for the differential thermal expansion between the two materials.
The burner block should not protrude beyond the hot face layer of insulation more than 13 mm. The refractory materials from which burner blocks are made will conduct heat to the lining materials. This will give shrinkage of this material and causing a gap, through which hot gases can reach the furnace shell. It is advisable in all installations to leave a space of about 100 mm around the burner. This 100 mm space should be packed with fiber or pieces of scrap blanket. The lining must be tight against the burner blocks on all sides. The figure 216 gives two methods.

Fiber wall modules
For easy mounting fiber wall modules are becoming very popular. Fiber wall modules are made from ceramic fiber blankets. A fiber wall module represents one complete lining unit of full wall thickness. In these modules the attachment system is not exposed to the furnace environment. The modules can be built up out of strips of ceramic blanket and are set on edge. The width of the strips corresponds to the lining thickness, see figure 217. The modules can also be built up out of folded strips or blankets to make up the module, see figure 218. This type of modules can in general with and in general higher maxim= temperatures.
As can be seen from the two last figures the blanket strips are adhered to an expanded metal backing. This enables a module to be quickly installed either as the complete lining of a new furnace or of an existing unit. Modules are fixed to the furnace shell (see figure 219).

**Burner blocks and ceramic modules**
As with layered blanket constructions fiber modules will not support the weight of a burner block. A burner support housing should be made as shown in figure 215. One or more folded strips should be wrapped around the burner block to insure a tight joint, see figure 220.

**Burner safeguarding**
Under this head we will only briefly discuss the principles of burner safeguarding through flame detection.

**Principles of flame detection**

We can distinguish three types:

1. the simple conduction by means of direct current;
2. method of the redressed alternative current;
3. methods based on flame radiation.

Also other principles are applied based on the use of bimetals or thermal electrical couples (thermocouples). These devices are often used to control atmospheric burners of low capacity, like water boilers, gas radiators etc. Due to the long safety time this method is not used for middle and high capacity burners like industrial burners.

For industrial burners above mentioned three principles of flame detection are applied.

Flame detection is done by means of electrodes or so called flame rods (see figure 221) and in the case of radiation pick up by scanners.

![Figure 221: Flame rod](image)

The use of flame rods to control the presence of a flame is based on the electrical characteristics of the flame. The gases in the combustion area are in a ionised state, thus conductors of electricity, due to the chemical reactions of the flame and due to the high temperatures involved.

1. Conduction by means of direct current

In this method a source of direct current feeds two electrodes in contact with the flame. Most of the time one of these electrodes is the burner mass (see figure 222). The principle of functioning is in fact to measure the resistance of the flame, if there is no flame the resistance between the two electrodes is approximately infinite. When there is a flame the resistance should stand into a few megohms. A galvanometric relay permits to order the electrical circuit of a fuel shut-off valve in the gas line. As can be seen there is no positive security. In fact, if the flame rod is in contact with the burner itself there is a flame simulation and the fuel shut-off valves remain open. For that reason this principle is not used anymore at the time.
2 Redressed alternative current method

Two electrodes with a different surface, in a ratio of 5:1 for instance, which are built into an ionised gas act like a redresser of alternative current. This redresser phenomenon depends on the dissymmetry of the electrode surfaces. An analysis of the conductivity of the gas flame will show us the reasons. The current passes through the electrodes by the means of a displacement of ions and electrons coming from the ionised gas. The displacement of the ions will affect the intensity of the passing current due to the electrons which are able to move faster than the ions. For more details see end of this part which explains the principles of ionization.

It is evident that in our case the number of ions capted by the burner during the first half period corresponding with the negative polarity of the burner is more important than the number of ions capted by the flame rod during the next half period. Figure 223 shows us in full lines the nature of the obtained current. The pointed line represents the average value of this resulting current.
Some practical points

- The electrode has to be positioned in the ionization zone of the flame. This zone is just after the flame front and the blue cone of the flame. This blue cone is called dart. The flame signal decreases at the end of the flame which is rich in combustion products. We can measure the flame signal by means of a micro ampere meter incorporated in the flame signal circuit. The value of the flame signal depends on the type of flame safeguard used and is generally situated between 2 and 15 microamperes.

- The value of the flame current has to be checked in several operating conditions of the burner. Maximum and minimum capacity of the burner and intermediate positions have to be checked. You have to be sure that the pilot flame guarantees the complete ignition of the main burner if flame detection is located on the pilot flame and continuous pilot is used. Therefore we prefer an interrupted pilot and controlling the presence of the main flame.

- We need a good isolation between the flame rods and the ground. The flame rod support has to be a good isolator and have a good temperature resistance. In general this material is porcelain or steatite.

- The wire between flame rods and flame safeguard has to be as short as possible and have as well a good isolation as a low capacity to the ground. The maximum capacity of the flame rod wire will be 0.02 micro farad. For this reason the wire shall not be passed into a metal hose or be of the coax type (blinée) type. Read carefully the instructions of the manufacturer of the flame safeguard before installing.

- The value of the flame current depends not only on the contact surface of the electrode but also on the ratio of air and gas. On the next figure 225 you can see the value of the flame current with different type of air/gas ratio.
- You can see that for $n = 1$ this means stoichiometric combustion the flame current is maximum. With excess gas (see left side of the pointed line) you can see that the value of the flame current drops rapidly. This means that we cannot use the system of flame rod to control the presence of a flame with burners that are firing rich.

You can also see on the graphic that an excess air does not affect the value of the flame current in the same manner as excess gas.

Advantage of this graphic is also that when the burning goes firing rich you will get a shutdown of the installation. This is in fact a positive security because if the burner goes firing rich it can be a dangerous situation. Lean gases, like cokes oven gas, give low ionization currents, so that the value of the current is not sufficient to control the presence of a flame. It is recommended to use another type of flame detector for this kind of gases. The most used gases like natural gas, butane and propane give us sufficient ionization and the flame rod can be used with good results to control the presence of the flame.

- The ignition transformer can disturb the flame current in certain cases. You can change the polarity of the primary of the ignition transformer to eliminate this problem so that the flame safeguard and the ignition transformer are fed by opposite phases.

Rules for good flame rod application

1. The flame current has to be stable. This can be controlled by means of a micro ampere meter in the flame current circuit. The variation in flame current shall not exceed the width of the meter point. This will guarantee a maximum signal and is an indication that the system is saturated.

2. Be sure to have a good ground surface. The ratio between ground and the electrode surfaces must be a minimum of 5:1. Always try to increase this ratio if it is possible.

3. Install always a ground wire between the burner and the flame safeguard to obtain a flame signal and to avoid parasite currents.

4. Use always a good isolated wire to transport the week current so that we are sure that the current enters the flame safeguard at a sufficient value.

5. The length of the flame current wire is limited by the capacity of his wire to the ground. Never exceed the capacity of 0,02 micro farad.
The resistance in the circuit of the flame current will not influence the good function of the flame safeguard. Nevertheless, this resistance shall not be more than 1 Mohm. An impedance has to be eliminated in the circuit.

Corrosion on the electrode or the flame rod will not isolate the electrode in presence of the temperature of the flame. The only effect will be that the surface between electrode and ground will decrease.

Flame rods will be located on such points on the burner where the temperature will not exceed more than 300 °C. Most of the isolated materials loose a part of their isolating characteristics beginning at 300 °C and resistance will decrease. Flame rods will also be mounted on such places where they stay clean. We shall clean the flame rods at regular times if we see that there is a lot of dirt on the isolator and on the flame rod itself.

We shall always control if the interference of the ignition stays in some limits. A decrease or an increase of half a microampere can be tolerated. We change the polarity of the ignition transformer if we see that the flame current decreases on the moment that the ignition transformer works.

**ATTENTION:** A FLAME ROD CAN ONLY BE USED TO CONTROL GAS BURNER, NEVER TO CONTROL THE PRESENCE OF AN OIL FLAME.

Devices sensible on flame radiation

Every flame produces infrared and ultraviolet radiation. Some flames like oil flames give us also visible radiation. Let us have a look now at the different types of scanners which are affected by the radiation of the flame.

**Infrared scanners**

The electrical resistance of lead sulphide decreases when it is affected by infrared radiation. When we use an infrared scanner in this way, it cannot distinguish the flame of a burner from the radiation of the warm refractory wall, which is in general used in steam boilers.

An alternating current passes through an infrared scanner when it is affected by infrared light.

The difference between infrared light emitted by a flame or by a body on high temperature is that the flame emits infrared light by intermittence and a body on high temperature is a continued source of infrared light.

The application circuits of a flame safeguard can be adapted in such a way that it reacts only on an intermittent infrared sign. This means that the infrared scanner will not be affected anymore by the radiation of the red hot refractory.

One of the advantages of the infrared scanner was that is was possible to control a gas and/or oil combination burner. As we have seen the flame detection by means of flame electrodes was only possible for gas burners. Nevertheless, the use of an infrared scanner is limited. Hot gases circulating in a combustion chamber can produce an intermittent infrared radiation and so simulate the presence of a flame. We do not have positive security and the infrared scanner can even be affected by sources of daylight. Especially when the combustion chamber in which the burner is mounted is not completely dark.

**Photo resistance scanners**
Certain materials like thallium or cadmium sulphide present the particularity to be a good or bad conductor of electricity if they are submitted to a light source. This sensibility to the light and to infrared radiation permits manufacturing of very cheap scanners who can be used to control burners with a flame who emits light. These scanners cannot discriminate light emitted by the flame or light emitted by any other source. The resistance variation in the flame detection circuit can be interpreted by the protector relais if there was a flame. These scanners can only be used on dark combustion chambers and for low capacity burners.

**Photo emitting scanners**
These are scanners which are composed by a vacuum tube with a cathode in cesium oxide mounted on silver and an anode.

Direct current passes these scanners if they are submitted to a light source.
An alternative current is fed on the two electrodes of such vacuum tube and when this vacuum tube is submitted to a light source a direct current comes out of this vacuum tube and then is passed into the amplification circuit of the flame safeguard who is transmitting his impulses to the flame relay. We can only use these scanners for burners mounted on dark combustion chambers and combustion chambers without refractory lining.

**UV scanners**
The main component of a UV scanner is a tube, filled with an inert gas, with a cylindrical form, which has the fundamental quality to emit electrons when it is submitted to a UV radiation. The wave length of this radiation is comprised between 1950 and 2600 Angstroms.

![Figure 226](image)

The flame safeguard relay interrupts 20 times /s. the potential difference between anode and cathode of the UV scanner to assure a good function and a positive security using this kind of scanner to control a burner. So we have to start the ionization in the UV tube 20 X/s. and this results in a positive security and a quick response time (safety time) of the installation.

The UV scanner is mostly used to control high capacity burners, burning different kinds of fuel, as natural gas, fuel oil, heavy oil, butane, propane.

This kind of scanners is insensible to radiations with a frequency higher than 2600 Angstöm. This means that they cannot be affected by refractory lining in the combustion chamber who is brought to high temperature by the visible light.

With this kind of scanner it is also possible to control a flame developing in open air.

**Ionization**
Ionization is the physical property of a flame produced by a fuel containing hydrogen. The flame produces a quantity of electrons coming from the gas molecules. Each of these molecules has then a positive load and becomes thus a positive ion (the load of an electron is negative).
An electrical current will flow between a metal piece and the burner if we bring such a metal piece with a different potential in the gas flame. This electrical current is the result of the moving electrons and ions in the electrical field formed by the different potential between burner and electrode.

This electrode is usually called flame rod. The free electrons move to the positive electrode and are repulsed from the negative electrode: the positive ions move to the negative electrode and they are repulsed by the positive electrode.

We can find on the surface of the negative electrode a number of electrons coming from the outside different potential that is applied. This is in fact the reason why this electrode is negative. These electrons repulse each other and we need only a small supplementary effort of a positive load to move these electrons in the gas flame. This effort is produced by the positive ions who are in the neighborhood of this electrode. The number of free electrons depends on the quantity of ions. It is the power of these ions who liberate the electrons.

A certain amount of these electrons combines again with the ions and forms neutral molecules. Nevertheless, the ionization process continues to liberate electrons from molecules forming new ions as long as the flame exists.

The quantity of electrons leaving the negative electrode and coming to the positive electrode is a definition for the intensity of the current. This intensity depends on the number of ions in the neighborhood of the negative electrode and these ions have to be powerful enough to liberate electrons from the negative electrode. The ions are heavier than the electrons and move thus slower. Only a part of the ions in the gas flame can approach the negative electrode and can act effectively during the 1/100 of a second of the first alternance. This is so because we have the distance between the two electrodes. This condition limits also the intensity of the flame current.

We will have the same intensity of current during a positive and negative alternance if the two electrodes have the same surface in contact with the flame. When we use the system this way we can simulate a flame and we will not have a positive security of controlling the flame. We will not have a direct component in the flame current. This is the reason why such security devices are not longer used.

Let us consider now an electrode in such a way that one of these electrodes has a surface several times greater than the other one. in this case we will have an effect of direct current. The two electrodes are the flame rod and the burner body. The surface of the burner body in contact with the flame has to be at least 5x greater than the surface of the flame rod in contact with the flame. Let us have a look at figure 227 and 228 for good comprehension of the system.
Figure 227 represents the phenomenon on the moment when the flame rod is positive and the burner negative. Most parts of the positive ions move to the negative surface and liberate an important number of electrons from this surface. The relative important current is indicated in the top left corner. The arrows show us the sense of moving of the electrons and the current, who are opposite.

Figure 228 shows us the phenomenon during the next alternance, while the polarity of the two electrodes is changed. The important surface of the burner does not reduce the distance between the two electrodes. The positive ions have to travel the same distance to approach the negative flame. Their efficiency is less important so that they cannot liberate the same amount of electrons and this results in a lower value of current. We can see at the top right corner the shape of this current. Although it is not completely a direct current but a pulsating current and the two alternances will give us the direct current component on which the protector relais reacts. A resistance variation will not simulate a flame and the flame safeguard will stop the burner if the flame rod is in contact with the burner. We have a positive security with this system.

IMPORTANT REMARK: FLAME DETECTION BASED ON THE PRINCIPLE OF IONIZATION IS ONLY POSSIBLE WITH GAS BURNERS.

Gas trains

Gas trains, also often called pipe trains, are supplied with shut-off valves, pressure regulator, strainer pressure switches etc. for the purpose to control the gas supply to the burner. Gas trains are composed to suit the needs of an application and the requirements of safety regulations.
Figure 229 shows a typical standard gas train for over 600 kW capacity burners. Burners with less than 600 kW capacity only have 1 shut-off valve for the main burner and for the pilot line as shown in figure 230.

Figure 230: Standard gas train for small burners

The size of the nominal pipe train diameter is mostly based on a maximum velocity of about 30 m/s.

The next table gives the amount of gas (m$^3$/h) which can flow through the gas train for different pipe sizes.

<table>
<thead>
<tr>
<th>Nominal pipe train size (&quot;)</th>
<th>Gas flow (m$^3$/h at 30 m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
</tr>
<tr>
<td>1 1/4</td>
<td>110</td>
</tr>
<tr>
<td>1 1/2</td>
<td>150</td>
</tr>
</tbody>
</table>
VII  BURNERS DESIGNED FOR CERTAIN APPLICATIONS

Burners discussed in the previous chapters could be used in many applications or in any case more than one application. For example, the premix fed line burners could be applied in heating tanks and vats and for air heating.
The burners discussed in this chapter are designed for just one type of application. Some examples of such burner application combinations are:

- immersion tube heating;
- incineration;
- supplementary firing in turbine exhaust streams.

In this chapter we will describe above mentioned burner application combinations in more detail.

Immersion tube heating

For heating water or more general for heating solutions several methods are used like underfiring, conventional immersion tubes and direct firing. All these methods will be described briefly.
Underfiring a tank as shown in figure 231 is simple.

Solution tank heating with pipe burner (Eclipse)

Solution tank heating with wheel burner

Figure 231
These types of burners are inexpensive and easy to install. A drawback is the low thermal efficiency of this system which is in general no more than 40 to 50%. This makes it expensive to operate due to which this system is only applied for small tanks. The efficiency can be improved by guiding the combustion gases through a double wall around the tank.

Conventional immersion tubes were very popular because rather good efficiencies can be obtained up to about 75%. Figure 232 shows a typical tank, immersion tube and burner arrangement with high-low burner control. For this type of application burners are available to fire immersion tubes as small as two inches nominal pipe size, all the way up to 14 inches.

![Standard series burner with hi-lo control (Eclipse)](image)

On high fire, both the solenoid valve and the bypass gas cock are open. For the low fire the solenoid valve closes and gas passes through the bypass only.

Figure 233 shows a nozzle mixing burner only designed for immersion tube heating. The gas nozzle and mixing disc inside the burner are designed to produce a very long flame thus ensuring even distribution of heat over the entire inner surface of the tube resulting in a uniform heat transfer. This burner is often applied for applications as large salt baths, pickling tanks, asphalt kettles etc. They are available in capacities ranging from 235 kW to 1450 kW and turn down ratios of 25:1. A high turn down ratio may be important for fast heating without overheating during holding periods.

High efficiencies require long immersion tubes. A 280 kW installation requires about 14 m tube length for 75% efficiency.
These types of burners often require rather large tube diameters and large radius elbows for return bends to minimize pressure drop. Still conventional immersion tubes remain one of the best and most efficient ways to heat a liquid solution.

Direct firing in a liquid solution can also be accomplished by submerged combustion. Submerged combustion is a method in which the products of combustion come in direct contact with the liquid being heated. The heating efficiency can exceed 100% of the lower caloric value of the fuel. Figure 234 shows a submerged combustion system using a nozzle mixing burner. As can be seen from the figure the flame is isolated from the solution, eliminating possible interruption of the combustion process.

For these burners sufficient pressure must be developed to overcome the liquid head and allow for all other pressure drops in the system. Very often a combustion air pressure is needed of 140 mbar to overcome 75 cm of liquid head.

To ensure complete combustion, the burner tube is cooled by the incoming combustion air. This preheats the combustion air and prevents flame chilling.

Combustion products enter the liquid through ports along an immersed distribution tube approximately 500-800 mm below the surface level. Heat transfer between the combustion products and the liquid being heated is excellent. 1 m$^3$ of products produce 6 mm bubbles in the
liquid having a total surface area of approximately 1000 m\(^2\) and the exhaust gases off the liquid surface leave at the liquid temperature. The efficiency aspect needs extra information. It is essential that the exhaust gases leave the liquid surface saturated with water vapor, whatever the liquid temperature may be.

Below the dew point of the exhaust gases (59 °C for stoichiometric combustion of natural gas) condensation of a part of the water vapor of the combustion gases in the bath will take place. This is called bath thinning. Below 55 °C the heating efficiency is over 100% on the basis of the lower caloric value of the fuel.

Above the dew point, evaporation of the liquid takes place and this in consequence is called bath concentration.

The phenomena can be neglected between 60 °C and 70 °C, however above these temperatures the heating efficiency decreases considerably (see figure 235).

For liquid temperatures above 60 °C other heating systems like immersion tube heating are recommended.

Figure 235: Effect of bath temperature in higher heating value efficiency

Another obstacle to more widespread use of submerged combustion is the possibility of contaminating the solution. In general all phosphate solutions and acid baths are safe. Weak alkaline solutions which are reviewed regularly also may be heated by submerged combustion. This method is not recommended for strong alkaline solutions.

The influence of combustion products on the liquid can further be described as follows. Apart from water vapor, other products of combustion are absorbed into the liquid until saturation point is reached. At 80 °C 15 mg CO\(_2\) per liter is soluble but only 5 mg per liter at 30 °C. The acidity in a neutral solution is decreased from pH=7 to pH=5 at which point a balance is reached due to saturation.

The influence of carbon monoxide (CO) can be neglected because with modern burners almost no CO is formed.

The described burner for submerged combustion is applied for water heating in the concrete and plaster industry, slaughter houses, green houses and heating waste water with aerobic water purification and the baths mentioned in the beginning of this part.

Burners are available in capacities ranging from 145 to 580 kW.

Another submerged combustion installation is shown in figure 236.
A recently developed alternative to above described conventional heating methods is the small-bore, high velocity immersion tube. Small-bore immersion tubes look like conventional immersion tubes except that for a given input, the tubes are smaller. One type of the small-bore system is shown in figure 237. In this system flue gases are transported with a high velocity through tubes of a small diameter. Advantages are improved heat emission averaging 50 kW/m² tube surface, against about 30 kW/m² with the usual systems. The construction gets more compact due to the smaller tubes. With this system a heating efficiency can be reached of 85 to 95% of low heating value depending of the tube length and the bath temperature. In general the combustion gases leaving the tubes are just 8 to 10 °C above the bath temperature. The bundle of tubes is built up out of 211 tubes. To obtain a high efficiency the straight length of these 211 tubes is about 10 to 14 meters.

Fume incinerators
Industrial exhausts can be polluted with particulate matter or with gaseous pollutants. Particulate matter can be removed by mechanical filtering which will not be discussed here. If we study the exhaust with gaseous pollutants we again can make a sub-division: exhausts polluted with organic hydrocarbons from users of industrial solvents, and exhausts polluted with anorganic material such as \( \text{SO}_2, \text{SO}_3, \text{NO}_x \) etc.

Purpose of this chapter is to discuss thermal incineration. A thermal incineration system is used in controlling emission of gaseous pollutants of organic hydrocarbon nature.

Several expressions are used for thermal incineration, like afterburner, fume incineration, thermal incineration.

Further in this paper it will become clear why we prefer to use thermal incineration.

**The oxidation process**

Exhausts of many drying processes are polluted with some kind of hydrocarbon mostly originating from a commercial solvent.

Typical emission process equipment using thermal incinerators are:
- fabric coated dryers;
- coated paper dryers;
- printing press dryers;
- litho ovens;
- metal decorating lines;
- paint and varnish process equipment;
- textile dryers;
- wire enamelling;
- fiberglass curing.

In many coating processes some kind of solvent or solvent water mixture must be applied to serve as a vehicle for the solids (ink or paint). in the dryer these solvents (moisture) are extracted from the substance by evaporation.

The dryer should be ventilated in such a way that any chance of explosion due to high solvent or hydrocarbon concentration is prevented. In practice this means that solvent concentration inside the dryer usually does not exceed 25% of the lower explosion limit (L.E.L.).

It will be clear that a manufacturer will try to work on minimum ventilation rates of his dryer, since any extra \( m^3 \) of fresh air supplied must also be heated.

Some dryers equipped with hydrocarbon monitoring devices are working on 40% L.E.L. levels to minimize make-up air supply.

The above will explain why pollutant concentrations in exhausts of dryers are always far below explosion limits.

For this reason exhaust gases from dryers can never be seen as a sort of low caloric gas which can be utilized in a burner.

The thermal oxidation process is based on oxidation of hydrocarbons on a temperature level high enough to accomplish the process within a second. More precise, the thermal incinerator process comprises a system in which exhaust gases with hydrocarbon pollutants are heated to a temperature beyond the self ignition temperature of the hydrocarbons in a surrounding with enough oxygen.
Auto ignition temperature is the temperature above which a combustible mixture of hydrocarbons with air must be raised to initiate combustion in the absence of a spark or flame.

Again in other words. Thermal incinerators destroy combustible pollutants through oxidation for which temperatures are needed of 750-800 °C to obtain nearly complete conversion in 0.1 to 0.3 seconds residence time. Destruction of most hydrocarbons occurs at 550-600 °C but oxidation of CO to CO$_2$ requires higher temperatures and longer residence times.

The oxidation process can be explained with the help of graph form figure 238.

In this graph the remaining hydrocarbon and carbon monoxide exhaust concentration is given as a function of the reaction temperature which is the temperature inside the reaction chamber. The residence time in the reaction chamber is 0.6 seconds. Line 3 shows mentioned function for white spirit which is a solvent with a very low auto ignition temperature (250 °C). Line A shows the line for toluene which has a rather high auto ignition temperature (535 °C). Line C gives the CO remaining in the exhaust as a function of the reaction temperature. The lines A and B are applicable for inlet concentrations between 2 and 12 grams per m$^3$. The graph is a result of many measurements.

Figure 238: Hydrocarbon oxidation curve
The following conclusions can be made:
- Beyond 650 °C reaction temperature almost all hydrocarbons are oxidized.
- For a proper removal of CO, a higher oxidation temperature is required.
- At 750 °C the remaining CO concentration will be about 100 ppm.
- Comparison of lines A, and B shows that hydrocarbons with lower ignition temperatures allow lower incineration temperatures to oxidize the hydrocarbons. The CO formed during any incineration or oxidation process requires a higher temperature.
- The most important conclusion, however, is that if CO begins to drop (lower than 1000 ppm) all hydrocarbons have already been oxidized.

If we compare the results of many measurements with the requirements of the German TA Luft then we may conclude that a 750 °C incineration temperature will give results to meet the German pollution law.

Heating of exhaust gases to oxidation temperature

A typical exhaust temperature of the process equipment from which emissions are controlled with thermal incinerations is 140 °C. These exhaust gases should be heated to 750 °C which is a temperature rise of 610 K. This heating will cost 3 to 4.5 times the amount of energy used in the dryer.

It is for this reason important to reduce the energy consumption with the help of heat exchangers. Sensible heat available at 750 °C level from the exhaust gases can be utilized to preheat the 140 °C exhaust gases.

However, ignition of hydrocarbons inside the preheater should be avoided. Careful investigation of the types of hydrocarbons possibly present is kept about 30 °C below the lowest ignition temperature.

Ignition (oxidation) of one of the hydrocarbons will give a temperature rise of the exhaust gases inside the heat exchanger. This rise will be in accordance with the caloric value and the weight in g/m³(0) of these hydrocarbons. The temperature rise mentioned will make the preheater less efficient. At rather high concentrations of hydrocarbons it will even be possible to burn up the heat exchanger. For most commercial solvents preheating up to 450 °C will be possible. Further heating from 450 °C to 750 °C will be done by the burner and the heat available from the solvents.

The burner will be described later in this article. The solvents may contribute considerably to the temperature rise of the exhaust gases.

For example toluene will give a temperature rise of about 27 °C for each gram present in the exhaust gases per ml. If, for example, the exhaust contains 7 grams toluene (about 15% L.E.L.) per ml exhaust gases the temperature rise given by the toluene is 7 x 27 = about 189 °C. The burner must add 750 - (450 + 189) = 56 °C.

Temperature rises per gram/m³(0) for a number of hydrocarbons can be found in the list of figure 240. In this list the molecule weights can be found as well as the L.E.L. concentration in volume percent and grams/m³(0) and the ignition temperature.

With only toluene in the exhaust, preheating up to about 505 °C will be possible. With a 189 °C temperature rise of the available toluene the gas burner must deliver 750 - (505 + 189) = 56 °C.

Figure 239 shows calculated temperature course described earlier.
From above we can conclude that heating of exhaust gases (to be incinerated) from a process is accomplished by:

**Figure 239**

**Figure 240: Solvent data**

From above we can conclude that heating of exhaust gases (to be incinerated) from a process is accomplished by:
-preheating the gases in a heat exchanger to a temperature level just below the lowest auto ignition temperature, utilizing the heat available in the exhaust gases from the incinerator;
-exothermal oxidation reaction of the hydrocarbons in the exhaust;
-the burner.

**main components in an incinerator**
The components we will discuss in general in this article are:
-the burner;
-the heat exchanger;
-the reaction chamber.

Figures 241 and 242 give two common constructions.
In the case of figure 241 the exhaust gases are transported by fan 1. Preheating of the exhaust takes place in heat exchanger (plate type) 2 which is situated on top of the reaction chambers.

The exhaust gases are fed through the burner at point 3 and are then coming into the reaction chamber 4 in which the oxidation of the hydrocarbons takes place. The hot (750 °C) and incinerated gases leave the incinerator through the heat exchanger where part (30-60%) of the sensible heat is utilized for preheating. The inside wall from the reaction chamber is insulated with high temperature resistant ceramic material. Due to the fact that the insulation is at the inside, the reaction chamber wall and support steel can be made out of mild or corten steel.

Between reaction chamber and outside wall an overpressure is maintained in comparison to the inside of the reaction chamber to prevent any leakage of hot combustion gases to the outside.

In the installation of figure 242 preheating of the gases to be incinerated is effected in a tubular heat exchanger 2, situated around the reaction chamber 4. Situated between the reaction chamber and the heat exchanger is a tubular flow through duct 6 through which the very hot (750 °C) incinerated gases flow before they enter the tubular heat exchanger. This is to prevent cooling of the reaction chamber. It is clear that the construction of figure 242 is made out of heat resistant material.

**Burner**
Line burners are the most commonly utilized burners. The burner shown in figure 243 is widely employed in incinerators of various manufacturers. The burner shown in figure 244 is also found in incinerators. These are all natural gas (or propane) burners with oxygen taken from the fume stream but they can be modified for low oxygen (below 16%) content fumes.
Gas enters through holes in the manifold pipes placed across the duct. Air (fume) for combustion enters through holes in mixing plates attached to the manifold pipe (figure 243) forming a V shaped passage. Figures 243 and 244 show the Maxon combustifume arrangement. Profile plates are used to block most of the area between burner and wall. The opening between profile plate and burner is based on 40 mm AP during operation. About 50% of the preheated exhaust gases will pass the burner. The other 50% will enter the V shaped combustion area to provide oxygen for combustion. The Eclipse types are of similar concept. As indicated in most incinerator applications the fume is essentially contaminated air and has adequate oxygen content (usually 15-20%) both for burning the necessary preheating fuel and oxidizing the contaminants.
Figure 243: Distributed burner with profile plates (Maxon)

Figure 244: Line burner (Maxon)
Large fuel savings are associated with using oxygen in the fume for combustion of the fuel rather than bringing in outside air which must also be heated to 750 °C.

The widest variation among different incinerator designs is how well they achieve their goal in raising all fumes to the required temperature, the required time and the required temperature uniformness. Most cases of poor performance (oxidation quality) are due to non-uniform temperatures.

For these reasons the line burners described (or distributed burner) are well suited for use in thermal incinerators since the flame is distributed across the fume inlet to the combustion chamber.
An incinerator burner applied for incinerator constructions as shown in figure 242 is shown in figure 247. This burner is often called a discrete burner for incineration. The working principle is the same as for the distributed burner.

**Heat exchanger**
This section describes methods and equipment designed to make use of the heat energy contained in the flue gases discharged from the incinerator, which would otherwise be wasted. A number of recovery methods are in use of have been proposed.

- a) Heat exchange may take place between the hot flue gases and the cool fume stream, using a shell-and-tube or plate type (recuperative) heat exchanger or a rotary regenerative heat exchanger and thus preheating the fume stream before it enters the incinerator.

- b) A portion of the hot stack gases may be returned or "recycled" to the dryer or process unit which is the source of the fumes.

- c) The hot flue gas heat may be transported into some other manufacturing process unit, either directly or indirectly by a heat exchanger to a circulating heat medium, such as oil, water or melted salt or to a steam generator for process steam, space heating or power generation.

Since heating a large fume stream to a temperature as high as 750 °C represents a major consumption of fuel energy and one that will continue indefinitely so long as the incinerator is operated, the economics and practicability of heat recovery should be weighted very carefully. Many factors must be considered.

- a) Is it feasible? Dirty or foul streams may render heat recovery equipment inoperative in a very short time. Plant heat balance may not allow for an effective use of recovered heat.

- b) Is it safe? On fume streams containing combustible material, excessive preheat by heat exchange with the fuel gas might lead to flammable or even explosive conditions, recycle of hot incinerator stack gases could introduce contamination hazards in the process or oven equipment.

- c) Is it reliable? If heat recovery equipment forces frequent shutdowns of the incinerator for cleaning and this in turn shuts down the plant unit, the economic value of any energy saving would be nullified quickly indeed.

- d) Is it economically justified? A proper economic evaluation should account for installed cost, operating costs (including fuel, operator and supervision, maintenance etc.) interest rates etc.
Table figure 248 summarizes the alternatives, the advantages and the limitations.

<table>
<thead>
<tr>
<th>Type</th>
<th>Effectiveness Ratio, ε</th>
<th>Additional Auxiliary Equipment</th>
<th>Limitations, Problems</th>
<th>Commonly Used For</th>
<th>Commonly Not Used For</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regenerative (recuperative) exchanger</td>
<td>up to 0.58</td>
<td></td>
<td></td>
<td>Chiller control, water treatment skills</td>
<td>Key fumes containing oils, costs, surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube type recuperative exchanger</td>
<td>up to 15</td>
<td>Safety controls:</td>
<td></td>
<td>Safety, burner control, flame control</td>
<td>Little space</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate type recuperative exchanger</td>
<td>up to 15</td>
<td>Extra burning, controls, auxiliary control</td>
<td></td>
<td>Plate steam supply, burner and heater</td>
<td>Little space</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process heat-exchange transfer unit</td>
<td>up to 15</td>
<td>Recompression, piping, pumps, controls</td>
<td></td>
<td>Process steam supply, burner, heater</td>
<td>Little space</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Figure 248

Heat transfer effectiveness:

The fume or exhaust gas and the flue gas streams have about the same mass flow rates and specific heats, so the temperature rise of the exhaust gas will be about the same as the temperature drop of the fume. Usually this is done in a shell-and-tube or plate type (recuperative) exchanger. In case of a tube type heat exchanger one stream passes through the tubes and the other stream passes over the outside. Usually the fume stream runs through the tubes, although manufacturers differ in their practice.

The maximum temperature difference is formed by the hot flue gas minus the entering cold fume stream. This is in figure 239 t3 - t1. At 100% efficiency the hot flue gases are cooled to the temperature of the entering fume stream. Or the temperature rise of the cold fume stream will
exceed the difference \( t_3 - t_1 \) at 100% efficiency. In practice the extent that above is approached gives the efficiency \( E \):

\[
E = \frac{(t_2 - t_1) \, C_p}{(t_3 - t_1) \, C_p} = \frac{C_p (T_{\text{fume stream leaving}} - T_{\text{fume stream entering}})}{C_p (T_{\text{flue gas entering}} - T_{\text{fume stream entering}})}
\]

The need for a simple structure usually dictates using what is called a cross flow arrangement. Although the exchanger can theoretically be made more compact by using small diameter tubes, the need for low pressure drop and easy cleaning usually dictates that all passages be approximately an inch across (also for plate type design) and tubes an inch and a half or even two inch.

From the standpoint of maximum heat recovery, the ideal arrangement would be a counter flow between hot and cold streams. The simplest and cheapest, however, is the cross flow and stacked or "multiple pass" cross, flow units approaching counter flow performance.

One very important point should still be mentioned. Since described heat exchangers will have parts or places where temperatures may exist of 600 °C and more, special care should be given to the expansion problem. For the sake of this article we will not discuss rotary heat exchangers waste heat boilers etc.

Figure 249 shows construction details of a cross flow and stacked plate type heat exchanger.

Figure 249: Cross flow plate type heat exchanger (AER)

Figure 250: Cross flow tube type heat exchanger

Minimum heat consumption (heat regain):
Thermal oxidation is often considered as energy wise, a very expensive method to clean contaminated exhaust gases. This is often true for the reason that in the past incinerators were often not equipped with heat exchangers or other means to safe energy.

In incinerators equipped with heat exchangers and integrated with simultaneous running processes, energy can be recirculated, accomplishing a much lower energy consumption. In many cases there will be even a pay back period for the investment for a complete incinerator system because of energy saving gained by the incinerator.

With the help of an example we will try to explain the above statement. Before we start with the example, the following points are important for minimum energy consumption.

- Preheating the exhaust gases as much as possible. If possible, preheating should go as far as 30 °C below the lowest auto ignition temperature.

- Also the solvents (contamination) give a temperature rise. The heating realised by the solvents and heat exchanger should go if possible so far, that the temperature rise effected by the burner will not be more than about 60 °C (see figure 239).

- Instead of a heat exchanger for preheating the exhaust gases, a steam or hot water generator may be installed to cool down the hot (750 °C) exhaust gases. This solution will be possible if there is a constant use for full steam production at the same time that the incinerator works.

- If possible the cooled flue gases (about 400 °C) from the incinerator should be recycled to the process unit.

It will be clear that integration of the incinerator in different processes means careful investigation which processes run simultaneously.

The most obvious solution is to recycle heat from the flue gas to the dryer or process where the contaminated gases are coming from. If after this solution heat is still available, other processes may be integrated to recycle heat too.

Example:

To explain given statement that also an incinerator can have a pay back period resulting from energy saving an example will be worked out. Figure 251 shows an integrated dryer fume incinerator. The dryer may be a coated web dryer. The solvents needed for transportation are evaporated inside the dryer by blowing hot air out of nozzles on the web. The exhaust fan extracts the needed amount of air out of the dryer from the recirculation stream. Let us assume that this exhaust air contains 7 grams of toluene per m³(0). The exhaust temperature from the dryer is 140 °C.

Air with toluene can be preheated up to 505 °C being the ignition temperature of 535 °C minus 30 °C for safety.

During oxidation the solvents will give off a 7 x 27 = 189 °C temperature rise (see figure 239). To reach 750 °C the burner must generate another 56 °C being 750 - 505 - 189 = 56 °C. Since the fume transported by the exhaust fan has about the same mass flow and specific heat rate as the flue gas flow coming out of the incinerator at 750 °C, the temperature rise of the fume is about equal to the temperature drop of the flue gas stream. The temperature rise was from 140 °C to 505 °C which is 365 °C. The flue gas from the incinerator will drop to 750-365 = 385 °C (see figure 239).
In general, heat consumption from dryers can roughly be estimated, based on what is needed to heat the make-up air for the dryer to exhaust temperature, plus 100%. For most dryers the make-up air mass flow is about 80% from the exhaust mass flow. If the exhaust mass flow is $A$, $0.8A$ should be delivered as heated make-up air to the dryer.

This temperature can be calculated as follows:

$$(140 - 20) \times 2 + 20 = 260 \, ^\circ\text{C}$$

(20 °C is ambient temperature).

This make-up air for the dryer can be heated by mixing 385 °C flue gases with fresh air to match the required temperature of 260 °C.

This method of heat recovery has successfully been used in many baking, curing and drying ovens. The oxygen in the stack gas is partly depleted, hence, the fume stream coming from the oven will also be reduced in oxygen content and the burner flame stability should be verified. However, there will never be any oxygen content problem if the recycled mass flow is less than 65% of the exhaust mass flow.

Use of this recycle arrangement would not be desirable if a liquid fuel containing sulphur, or other corrosives were to be encountered in the system.

We assume that the fresh make-up air has a temperature of 10 °C.

Fresh air mass flow ($B$) + recycled mass flow ($C$) = 0.8 $A$.

$$10 \times 3 + 385 \times C \times 0.8 \times A \times 260$$

$B + C = 0.8 \times A$

$C = 0.8 \times A - B$

$$10 \times B + 308 \times A + 385 \times B = 208 \times A$$

$$375 \times B = 100 \times A$$

Mass flow fresh air $B = 0.267 \times A$

Recycled should be $0.8 \times A - 0.267 \times A = 0.533 \times A = C$
The exhaust or flue mass flow leaving the integrated installation will be \( A - 0.533 A = 0.467 A \) at 385 °C.
Without incinerator the heating of the make-up air would consume
\[
(26010) \times 0.8 A \times Cp = 200 \times A \times Cp \text{ kJ/s.}
\]
\((Cp = \text{specific heat in kJ/kg °C})\)

The energy consumed by the incinerator is 56 \( A \times Cp \text{ MJ/h. With full integration as described above (see also figure 252) the dryer will be completely fed with energy from the incinerator. The total result is that the integrated dryer will save energy in comparison with the dryer working without incinerator. The saving will be:}
\[
(200 - 56) \times A \times Cp = 14.4 \times A \times Cp \text{ kJ/s.}
\]

Note that for the sake of this explanation we assume all \( Cp \)-values to be the same. Small mass volume changes are disregarded as well.

Even more energy can be recovered from the system by further cooling the remaining 0.467 \( A \) mass flow at 385 °C by heating thermal oil or water for another process which can be integrated in the system.
In figure 252 we have indicated all the values.
**Oil versus gas fuels**

The burning of oil further complicates the combustion process. Because of the fact that oil must be atomized, oil burners for incinerators are always forward flame burners, using single or at most two or three burner units. Gas burners can be constructed as line burners giving a nice distribution of the flame and consequently good mixing of exhaust gases and combustion products. Oil burners often generate substantially higher levels of nitrogen oxides than gas burners. Oil burners require more frequent maintenance than gas burners. The most important point is that there is a considerable economic incentive to use the fume as oxygen supply for combustion. This can only be done by using gas. With oil burners a major part of outside combustion air must be delivered with the help of a combustion fan. All this combustion air must be heated to 750 °C. The saving in fuel by using oxygen in the fume stream without additional air, as can be done with gas line burners, is about 30%.

**Supplementary firing in turbine exhaust streams**

During the last 15 years the combination of a gas turbine with generator or compressor on one hand, with a waste heat boiler or drying process on the other, has been increasingly applied as a result of rising fuel prices. In numerous instances these so called co-generation plants have proven themselves an excellent investment. In most co-generation plants a supplementary firing system will be installed, using the oxygen in the turbine exhaust stream as combustion air. The purpose of supplementary firing on waste heat boilers is usually:

- to control and maintain the superheater steam temperature;
- to control the steam production;
- to increase the steam production.

In most cases a combination of the above-mentioned purposes will be aimed at. Therefore the supplementary firing system is a vital element in a co-generation plant: the reliable operation of the total plant largely depends on the type of supplementary firing selected.

![Figure 253: Arrangement of a gas turbine and waste heat boiler](image)

Figure 253 schematically shows the arrangement of a gas turbine and waste heat boiler and includes a supplementary firing system, executed as a duct burner.
This type of burner consists of a large number of line burner sections to give evenly distributed energy across the section of the duct. Figure 254 shows this type of burner in more detail. This type of burner will generally be applied up to a supply temperature of 800-850 °C, in which case the boiler manufacturer selects an uncooled duct between gas turbine and a convection type of waste heat boiler. Uncooled ducts are applied up to about 850 °C. These ducts are insulated at the inside.

Figure 254: Line burner for supplementary firing (De Jong Coen)

Figure 255 shows a burner for heating turbine exhaust gases up to about 1400 °C. The body of this burner is cooled by the boiler water tubes. In this case of high temperatures the boiler manufacturer selects a water cooled furnace. As can be seen the design of supplementary firing burners is very different from conventional burners in normal steam boilers which are designed to operate on low excess air.

Figure 255: Supplementary firing in a water cooled furnace wall (intertube type) (De Jong Coen)
For the purpose of a good and reliable operation of co-generation plants supplementary firing systems have to fulfill the following requirements:

- Low pressure drop across the burners.
  The total pressure loss across the burner and boiler is important to the efficiency of the gas turbine and has to be kept on an acceptable level. As known overpressure behind the gas turbine will cause lower efficiency.

- Uniform heat distribution at boiler inlet.
  This is required to obtain a uniform heat load to the boiler convection banks and to avoid hot spots, which can damage finned water tubes or superheater tubes.

- High turn down ratio for operating flexibility.
  This is to avoid unnecessary switching on and off of the burners depending on steam load.

- The supply to the burner of auxiliary combustion air for cooling or ignition should be avoided if possible, because this has a direct negative effect on the boiler efficiency, since this air has to be heated to stack temperature.

- Reliable operation without unexpected shut downs.
  The shutdown of a burner installation, caused by damage inside the duct, can result in a shutdown of the total plant for several days required for cooling down and repair of the burner, causing a considerable loss of production and, as a result, money.

- Low NO\textsubscript{x} design, preferably reduction of GT-NO\textsubscript{x}
  To fulfill today's requirement for air pollution, the design of the supplementary burner has to be such that NO\textsubscript{x} will be reduced as far as possible, without the formation of new NO\textsubscript{x}.

- Since the turbine exhaust flow is in most cases very uneven the burners must be of very rugged construction able to withstand high turbine exhaust gas velocities.

- The combustion of these burners should be complete without formation of CO and C\textsubscript{n}H\textsubscript{m}.

Above-mentioned requirements are fulfilled by many of the burner suppliers.
Figure 256 shows a cross sectional view of the burner casting and gas manifold pipe of the burner shown in figure 254.

As the gas exits from the orifice in the manifold, the jet expands and a portion is "peeled-off" by the edge of the exit hole in the casting. The flame is anchored by substoichiometric combustion in this area, marked "A". Combustion air is provided in zone "All via a small slot between the casting and the manifold. As the burner jet exits into zone "B", peak temperatures are suppressed by recirculating eddies of combustion products behind the wings of the stabilizer. The flame body than expands into the turbine exhaust gas stream where combustion is completed.

Figure 257: Intertube burner cross section (De Jong Coen)

Figure 257 shows a cross sectional view of the burner casting of an intertube burner as shown in figure 255.

The operation of the intertube burner, figure 257, is similar. Here we also have the premix zone "All and recirculation of flue gases in zone "B". The maximum capacity of a 15 cm section of these burners is 400 kW giving a flame length of about 3 m. The minimum oxygen percentage needed in the GT exhaust gas is 15%.

Figure 258 shows another burner for supplementary firing of turbine exhaust gases.
Minimum oxygen contents of exhaust gases is 13%. Outlet temperature should not exceed 900 °C. The temperature limit for the turbine exhaust gases passing the burner is maximum 650 °C. As with all the described line burners also with this burner many burner configurations can be made to obtain even energy supply, see figure 259. The maximum capacity per 30 cm burner is about 200 kW. The normal turn down ratio is 5:1. The process air ratio is 2:1. The line burner is lighted at one end and safeguarded at the other end, see drawing. The burners described before in figure 169 are also applied for turbine exhaust heating.
Figure 259: Typical installation of a supplementary firing burner (Eclipse)
CHAPTER VIII  SPECIAL BURNERS

In this chapter special burners will be discussed. They are not burners as described in chapter VIII, being burners for special applications. The burners described in this chapter may also be called modern burners, because most of them were developed during the last ten years.

About the following burners we will give some information:

- recuperative and regenerative burners;
- reduced and low NO\textsubscript{x} burners for air heating;
- pulse combustion.

Recuperative and regenerative burners

Energy consumption in ovens and furnaces can be diminished by applying a number of modern techniques. Some of these techniques are:

- Improving of the circulation inside the oven or furnace to get a better temperature uniformity and a better heat transfer. This point has been mentioned when discussing the high and medium velocity burners.

- Better and more close control of the fuel/air ratio (see figure 130).

- Diminishing of oven and furnace heat losses and heating times by applying modern insulation materials. This point has briefly been discussed in the part where we described the fibre insulation materials.

- Improving of radiant heat transfer, which which can be important for some processes like galvanizing tanks. The radiant heat transfer can be improved by applying flat flame burners. These flat flame burners were described in the chapter about nozzle mixing burners.

- Diminishing of oven and furnace heat losses by regain of the heat available in the exhaust gases.

The last point will be described further in this chapter.

Combustion air preheat

Even on well constructed and well operated furnaces, the major source of heat loss is in the flue gases, which often leave the furnace chamber at a temperature above that of the process. They are sometimes used to preheat the incoming material on continuously operating plant. Even when this is done thermal efficiencies of 40% are rarely achieved and 10% is typical on batch furnaces.

In principle, the heat leaving in the flue gases can be recovered and used to preheat the combustion air. This has been occasionally practised, particularly in the early post war period, using metallic recuperators mounted on the flue. These systems have not been favoured because of large size, high cost, maintenance problems and operational difficulties in controlling air/fuel ratio and in ducting hot gas to and from the recuperator.

However, for some applications recuperator burners cannot always be applied like in the case of oil firing or very low calorific gases. For this reason central recuperative systems are still applied.
Recuperative burners have been developed which, in a single compact unit, combine the functions of a burner, flue and recuperator. They overcome therefore the disadvantages of large size and the need to duct hot gases which occur with conventional recuperators. This makes installation more convenient and offers potential to reduce costs. The difficulties which remain are those of providing durability and reliable operation of components exposed to gas temperatures of 1350 °C or more in the recuperator and up to 2200 °C in the combustion chamber.

As mentioned the flue losses from furnaces is the major source of heat loss. The gross flue losses for natural gas are shown in figure 260.

![Figure 260: Gross flue losses of natural gas](image)

The losses increase with flue gas temperature. At 1300 °C, a typical temperature in steel reheating or ceramic firing, 70% of the energy input goes to waste in the flue products. If unnecessary additional excess air is present, losses are even higher. A striking example of additional heat losses caused by variations in air/gas ratio is illustrated in figure 261.
In the past, the incentive for preheating combustion air was to achieve sufficiently high flame temperatures for high furnace temperatures in the glass of steel melting. Nowadays more emphasis is placed on the efficient use of energy. Two approaches for preheating combustion air at the burner are:

- **recuperation**;
- **regeneration**.

With recuperation a heat exchanger is applied to regain the heat. Regeneration is where a material mass is used to absorb heat from the flue gases, prior to giving it up to the combustion air. This can be done by switching the air and flue gas streams such that their paths alternate, after a timed interval.

Fuel savings that are achieved by preheating combustion air by heat regain out of the flue gases is shown in figure 262.
From the graph can be seen that for a furnace flue temperature of 1400 °C air preheating to 600 °C will reduce fuel consumption with about 40%. The higher the process temperature, the greater the proportional fuel saving for a given level of air preheat.

With many of the present designs the flue gas temperature at the burner after passing the recuperator will be about 60% of the furnace temperature. This means that flue gases from a furnace at 1000 °C will be cooled in the recuperator to about 600 °C. The fuel saving will then be about 20%.

With present metallic materials the maximum heat exchanger metal temperature is around 1000 °C for longer operation.

**Recuperative burners**

Some years ago the recuperative burner has further been developed by Midlands research station of British Gas Corporation. The recuperative burner combines the functions of a burner and flue recuperator. Hot combustion gases out of the furnace are transported through a heat exchanger built in the burner. Combustion air flows in counter flow through the heat exchanger.

Figure 263 shows a recuperative burner design. This burner can be delivered in a capacity range up to 2000 kW.
The recuperative burner can up till now only be applied for gas fired installations. Recuperative burners have shown interesting for application temperatures between 800 °C and 1400 °C. Burners are constructed for low, medium and high velocity issue of the combustion products. As stated before high velocities promote good circulation and rapid heat transfer. Depending upon the furnace pressure the furnace flue gases are transported through the recuperative heat exchanger of the burner with the help of an air jet eductor located near the burner flue gas outlet. The air jet eductor can be driven by air from the combustion fan. It will be clear that material choice is an important point for the recuperative heat exchanger. Beside of the temperature point there are also consequences for the heat exchanger if the flue gases out of the furnace are fouled. Flue gases from a glass furnace for example contain natrium sulphate which will shorten the recuperator life. In these cases modern coating technics can help to protect the recuperator. Some burners are constructed in such a way that the recuperator can be replaced.

Figure 264 shows a modern design of a recuperative burner where the heat exchanger is built up out of cast iron parts provided with ribs. This burner can be delivered in a capacity range up to 250 kW.
Figure 265: Recuperative burner (Rekumat)

Figure 265 shows a modern high velocity recuperative burner. The recuperator is made from cast CrNi steel and is suited for operating at flue gas temperatures from the furnace up to 1300 °C. Above about 1100 °C not all the flue gases from the furnace are drawn through the recuperator to temperature safeguard the recuperator. The burner can be fed with a wide range of gases ranging from coke oven gases to butane or propane. The burner can work under excess air conditions up to 100% and excess gas up to 15%.

Air preheating at nominal load ranges from 55% to 65 % of the waste gas temperature. Approximately 700 °C air preheating can be achieved at a furnace temperature of 1100 °C giving a fuel saving of about 32%. The burner can be delivered in capacities ranging from 40 to 200 kW. The combustion air pressure needed for these burners is 80 mbar. Recent information indicate that higher combustion air preheat temperatures can be achieved with these burners when provided with ceramic heat exchangers.

The burner nozzle comprises a design where the combustion air is provided in stages. With this design a much lower NO\textsubscript{x} production is accomplished. The level of the NO\textsubscript{x} (NO + NO\textsubscript{2}) produced by burners has recently be described in air pollution laws in different countries like Germany, The Netherlands and Japan.

Figure 266: NO\textsubscript{x} emissions of recuperative burners
Figure 266 shows a graph in which the Japanese and German laws are indicated. In this graph can also be seen that the shown Rekumat burner has a lower NO\textsubscript{x} production in comparison to burners without combustion air provided in stages. Without going into too much detail, regarding the influences in combustion due to which NO\textsubscript{x} is formed, some points can be mentioned. The level on which NO\textsubscript{x} will be produced during combustion is dependent upon first of all the temperature level. Further are important the oxygen percentage in the flame and the dwell time. This means that at higher combustion air preheat temperatures higher NO\textsubscript{x} productions can be expected. For this reason low NO\textsubscript{x} design for recuperative burner becomes important.

**Regenerative ceramic burner**

The discussed recuperative burners are limited in the amount of heat they can regain from the furnace flue gases. For most burners the preheating of the combustion air was limited to 600 to 700 °C.

Because of the much larger surface area in a regenerator compared to a recuperator of the same volume the heat recovery of a regenerator is much greater than that of a recuperator. With regenerative heat exchanger out of flue gases of 1000 °C and 1400 °C air preheat temperatures can be reached of 925 °C and 1260 °C, giving fuel savings over cold air systems of 42-65% (see graph figure 267 and figure 268 showing the performance and characteristics).

![Figure 267: Possible fuel savings compared to a cold air system with 10% excess air (Stordy)](image)

![Figure 268: Performance and characteristics of regenerative ceramic burners](image)

The principle behind the regenerative ceramic burner system is the use of two burners, each connected to packed beds of ceramic material to form regenerative heat exchangers. These are heated by the hot flue gases and cooled by the combustion air as the burners are fired alternately. When one of the burners fires using cold air fed to the base of its regenerator, the waste gas is drawn through the other burner and down into its associated regenerator to preheat the packing, than exhausted to atmosphere. When the regenerator being heated is sufficiently charged, the reversing system is brought into operation automatically, allowing cold air to flow through the
newly heated regenerator, the air being preheated as it flows. The previously cooled regenerator then being reheated by the exhaust gas generated by the burner in the firing mode.

The burner changeover is automatically controlled from the predetermined bed temperature or from a typically 1-4 minutes time cycle. Flow direction is switched by a reversal valve connected on the cold side of the regenerator. One complete R.C.B. unit comprises two regenerators, two burners, a reversal valve and its associated control system. Each burner has its own flame failure monitoring system and is interlocked for burner start sequencing.

Figure 269: Schematic layout of regenerative ceramic burners (Stordy)

Reduced and low NO\textsubscript{x} burners for air heating

Industrial drying processes can be divided into direct and indirect processes.

In the former, the gas used for drying, normally ambient air, is heated by mixing it with hot flue gases produced by the combustion of a fuel, in the vast majority of cases light fuel oil or gas. These burners were described in the chapter about nozzle mixing burners.

As a result of this mixing, the drying air contains combustion products and these come into contact with the product undergoing drying.

In the latter type of process, the drying air is heated by means of air heaters in which there is in all cases a physical separation in the form of a heat exchange surface between the combustion products and the drying air. In this type of process, therefore, the drying air contains no combustion products.

In industrial applications the direct drying process is preferable to the indirect method because it offers the following advantages:
- lower capital cost;
- lower fuel consumption;
- less maintenance.
When drying foodstuffs, however, there can be objections to the direct process on public health grounds. For example, when products containing protein come into contact with NO\textsubscript{x} in the combustion gases, harmful nitrosamines may be formed by the reaction of the amines with the nitrogen oxides (NO\textsubscript{x}) in the combustion gases.

After above was recognized all in this book mentioned manufacturers started doing developments to reduce the NO\textsubscript{x} (NO + NO\textsubscript{2}) production of their burners. One method to reduce NO\textsubscript{x} production is to premix an excess amount of combustion air with the fuel gas. With pure methane the air/fuel ratio is about 14:1 (45% excess air). This air rich mixture is fed to a line burner type as described under "line burners with partial air supply". Figure 270 gives a typical installation scheme of such an installation.

![Figure 270: Reduced NO\textsubscript{x} line burners arrangement (Maxon)](image)

The capacity per foot (30 cm) of line burners should be kept to a maximum of about 140 kW. With described approach a NO\textsubscript{x} level of about 8 mg/MJ has been reported.

Another approach to reach reduced NO\textsubscript{x} levels is by situating two line burners in series as shown in figure 271.

![Figure 271: Low NO\textsubscript{x} arrangement (Maxon)](image)

The line burners applied here are of the type without combustion air supply. As shown in figure 271 the heating of the air should be obtained in two steps being a first step of 67% of the needed capacity and a second step of 33%. With this system a NO\textsubscript{x} level of about 2.5 mg/MJ has been reported.

The new requirement for minimizing the amount of combustion NO\textsubscript{x} discharged from burners for air heating became apparent in 1979 after above-mentioned recognition. A NO\textsubscript{x} concentration in the order of 0.05 ppm in gases used for foodstuffs drying purposes is now seen as the permissible maximum. This means that combustion gases at the burner mouth may average no more than about 1 ppm of NO\textsubscript{x}. In 1979 this would have been an impossible low level.

Referred to stoichiometric conditions, the NO\textsubscript{x} concentration in flue gases produced by conventional burners is in the range of 50-80 ppm. In recent years a number of manufacturers, such as Stordy, Ludwig-Ofag-Indugas and Urquhart have developed burners especially for use in direct drying processes which offer a drastically reduced nitrogen oxides (NO\textsubscript{x}) production. For example, Urquhart has introduced a burner which, according to their data, gives an NO\textsubscript{x}
concentration in the flue gases, referred to stoichiometric conditions, not exceeding 2.3 ppm (1.1 ppm).

Without going into the complicated mechanism of NO and NO₂ forming we will only mention that NO is progressively formed in a flame above 1100 °C flame temperatures. More NO will also be formed at more excess air and the longer the gases spend at high temperature. The temperature influence however is by far the most important one.

Design considerations that reach the 1 ppm NOₓ level as described are low burning temperature, low oxygen content and short duration of upper temperatures. Since the temperature influence is the most important one, extreme low flame temperatures will also produce very low nitrogen oxide levels. In order to achieve this low flame temperature, the gas has to be premixed with a large proportion of excess air. Since even locally higher temperatures (hot spots) can have a disastrous effect on the final result, this mixing must be as perfect as possible.

Furthermore, the optimum gas / air ratio has to be kept as constant as possible over the burner's entire operating range, necessitating control of the gas/air mixing ratio. The gas and air are mixed by means of ejectors. These are driven by the combustion air. Gas is drawn from the gas inlet chambers via drillings in the slot-shaped throats (see figure 272).

A schematic diagram of the gas/air ratio control is given in figure 273. The gas rate is controlled as a function of process temperature. The regulator primarily controls the volume of combustion air and hence the air pressure in the ejectors. This pressure ensures at all times that the correct volume of gas is drawn in to give the same gas/air ratio, irrespective of the burner output. As will become apparent, this burner has been designed on the basis of an air factor of approx. n = 1.7. This corresponds to a premixing of 1.7 x 8.5 = 14.5 m³ air per m³ Groningen natural gas.

To ensure complete combustion, there has to be an adequate residence time within a homogeneous temperature field. The high premixed air ratio yields a weak mixture and hence a a "lazy" flame. To ensure complete combustion in these conditions, the burner incorporates a long combustion chamber clad with a fire-resistant lining. The overall residence time of the combustion products in the combustion chamber of the burner under investigation was slightly less than 0.1 seconds at full output and about 0.3 seconds at low output levels. The cross section is tapered to give a conical burner outlet, which increases the exit velocity.
For applications requiring a wide control range, a two-stage version of this burner is available. In this form, the control range is 1:10, compared with a claimed range of 1:5 for the single-stage version.

The burner is available in five different ratings, from 700 kW to 4400 kW. In the two-stage version, the mixing and combustion take place in concentrically arranged spaces, i.e. an outer annulus and an inner tube.

A premixed pilot burner is fitted within the inner combustion chamber. To obtain a constant and stable flame, this pilot is designed to burn at a lower excess air ratio than the main burner. The pilot burner is in continuous operation. There are two UV cells, one protecting the pilot burner and the other protecting the main burner flame. Other safety devices take the form of fusible links in both mixing chambers to safeguard against lighting-back or burning overheating.

Test results on NO\textsubscript{x} production

The burner was tested in several laboratories as the Gasunie laboratory. In the following graphs the most important results are given. All the flue gas NO\textsubscript{x} concentrations given are exclusive of concentrations of NO\textsubscript{x} already present in the combustion air.

A study of NO\textsubscript{x} concentrations of ambient air shows a variation of 17 to 12 ppb with a mean of 40-45 ppb. Peaks of very short duration, such as those caused by cars passing the sampling point, were over 250 ppb. In some heavy industrial areas with no wind levels of 600-800 ppb have been recorded.

NO\textsubscript{x} concentrations were measured at different excess air ratios and gas rates. Figure 274 shows test results at maximum firing rate. At air factors between n = 1.6 and 2.0 the NO, NO\textsubscript{x} and CO concentrations are given. From the graph can also be seen that the burner became unstable at an air factor lower than n is about 1.6 and n is higher than 2.

NO\textsubscript{x} concentrations from 2 to almost 5 ppm were found at low excess air ratios. At excess air ratios above 1.85 a sharp rise in CO production was observed. The proportion of NO2 was found to be half or slightly over half the total NO\textsubscript{x} content.
Figure 274

The graph of figure 275 shows the comparison between low NO$_x$ and conventional burners.
From the graph can be seen that at a given rate, conventional burners produce 30-60 mg/MJ of NO\textsubscript{x}, whereas the low NO\textsubscript{x} burner produces 1 mg/MJ.

**Conclusions**

Using this burner, a flue gas NO\textsubscript{x} concentration of 2.3 ppm (referred to stoichiometric conditions) can be achieved. When these flue gases are used as a drying medium, they will as a rule have to be diluted with air to reduce them to the desired temperature of 80-100 °C, i.e. a 30-fold to 40-fold dilution. If the flue gases could be diluted with NO\textsubscript{x} free air, then the drying medium would not contain more than 60-80 ppb NO\textsubscript{x}. Since, even in environmentally favorable areas, the ambient air NO\textsubscript{x} concentration can on occasion reach this order of magnitude, it can be concluded that this design of burner does achieve the minim\textsubscript{=} level of NO\textsubscript{x} production.

Another low NO\textsubscript{x} burner for air heating applications is shown in figure 276.

**Figure 276: Low NO\textsubscript{x} burner (LOI-SiNOx)**

Figure 277 shows a graph in which test results are given from the LOI burner. From this graph can be seen that excess air amount, NO\textsubscript{x} and CO production are the same.
Figure 277: Test results on LOI burner

Figure 278 shows a principle of a low NO\textsubscript{x} burner mounted for recirculating air heating in a malt kiln.

Figure 278: Malt kiln with low NO\textsubscript{x} burner

Another reported low NO\textsubscript{x} burner is shown in figure 279. Whereas the described real low NO\textsubscript{x} burners from Urquhart and LOI were forward flame burners, the Stordy burner is a line burner. Air heating line burners in general will better distribute the supplied energy. From this burner no test reports are yet available. The capacity per foot (30 cm) of burner is about 210 kW. The turndown ratio is at least 4:1.

Figure 279: Low NO\textsubscript{x} line burner (Stordy-Nu-Way)

Pulse combustion
Pulse combustion is still a very new technic. Pulse combustion for industrial applications such as drying is at the moment in the development stage. For this reason we will only briefly discuss pulse combustion.

The principle of pulse combustion was used by the Germans during the World War II in their V1 rockets.

The pulse combustion system is schematically shown in figure 280.

![Figure 280: Basic pulse combustor](image)

The start of activity occurs in the combustor where the air and gas are initially ignited by a spark or glow coil. The combustion creates a positive pressure in the combustion chamber, thereby closing the air and gas flapper valves.

With increased pressure the combustion products exit through the tail pipe. With this flow the pressure in the chamber falls below atmospheric pressure, opening the air and gas flapper valves and drawing in fresh charge of air and gas.

This fresh charge is automatically reignited by the hot gases remaining in the combustor and the cycle is started again. Once started the burner no longer requires a starting air blower or an igniter and operates as a self-powered burner. To achieve good combustion characteristics a mixer head is attached to the front of the combustor to assure that uniformly mixed gas and air is supplied to the combustor. A conventional spark is mounted in the mixer head for starting the process. This igniter is also used as a safety device to sense that combustion is occurring.

Pulse combustion burners generate noise due to the fact that they resonate at frequencies between 20 and 100 cycles per second. This noise can be reduced to acceptable levels by using properly designed inlet and exhaust the so called decouplers. Decouplers also effect the operating characteristics of the burner.

The described pulse combustor is designed for applications such as space heaters, water heaters and deep fat fryers.

The main advantage of pulse combustion is better heat transfer due to the oscillating pressures associated with this type of combustion.

The increased heat transfer from the hot gases to the surrounding walls means more heat from the gases with the same surface.

If in industrial direct drying applications a pulse combustor is applied an improved heat transfer around the drying particles can be expected. Due to this high drying efficiencies are reported (3000 kJ per kg water evaporated). Products like fish meal were dried with pulse combustion dryers. It has been reported that pulse combustors can handle materials that are sized from microns to 6 mm, as well as slurries ranging from 1% to 99% solids.

Figure 281 shows a schematic of a drying installation with pulse combustor.
The working of the dryer can be described as follows.

At the heart of these systems is a specially configured hollow tube whose shape and material of construction determine its operation. The process is initiated when air and fuel are drawn into the combustion chamber and ignited. Hot gases generated by the resulting detonation move at high velocities from the combustion chamber.

Detonation causes the pressure to rise in the combustion chamber, momentarily shutting off the fuel supply, which is maintained at a constant low pressure. This pressure fluctuation results in very strong standing waves of sound energy that, like the beat waves, move away from the combustion chamber. Then, as the pressure falls, fuel and air re-enter the chamber and are once again detonated with a spark.

The process is continuous, the rate of detonation depending on the geometry of the combustion chamber (ignition systems are also used in some systems). These rapid detonations create adequate turbulence to atomize most materials entering the drying cone of the combustor, while the sound waves initiate a scrubbing action that aids in the evaporation process. Once the wall surface reaches operating temperature, the spark is no longer required and the process becomes self-igniting.
**IX APPLICATIONS**

Many applications were already mentioned and described in the previous chapters. At the end of this book in the appendix a list of described applications is given. This chapter about applications will have two parts. The first part will handle about burners for drying applications and the second part about burners for oven and furnace applications.

**Dryers**

Here we will briefly discuss the most important dryers after which we will discuss the burners which can be applied for each of the dryers. Dryers can be divided in three groups.

**Direct dryers**
Heat transfer for drying is accomplished by direct contact between the wet solid and hot gases. The vaporized liquid (often water) is carried away by the drying medium being the hot gases. Very often the name convection drying is used here.

**Infrared dryers**
Infrared heat transfer has been discussed in chapter III.

**Indirect drying**
Heat for drying is transferred to the wet solid by means of a heated surface. Rate of drying depends on the contacting of the wet material with the hot surface. The vaporized liquid is removed independently of the heating medium.

Since this book handles about burners in general and also about burners for industrial air heating we will only describe convection or direct dryers here. As mentioned infrared heating and drying has in general been discussed in chapter III. Indirect dryers are mostly fed with thermal oil or steam from central boilers. Boilers and boiler burners are not a part of this book and for this reason indirect dryers are also not discussed here.

Convection drying is the most common method of drying. Convection drying can be divided in continuous and batch types.

Some continuous dryers are:
- flash dryers;
- spray dryers;
- continuous tray dryers;
- continuous sheet of web dryers;
- fluid bed dryers;
- tunnel dryers;
- rotary dryers.

Some batch type dryers are:
- tray and compartment dryers;
- fluid bed dryers.

In the following pages we will describe some of these dryers in relation to the burners which should be selected.

Flash dryers (pneumatic conveyor dryers)
Figure 282 shows a typical flash dryer.

These dryers are called flash dryers because drying is rapid, almost instantaneous. They are also called pneumatic dryers because in most cases the quantity and velocity of the gas are sufficient to lift and convey the solids. In its simplest form a flash dryer consists of an air conveyor system using heated air. As mentioned drying is very fast (less than 1 s). Wet particulate solids are simply dropped into a moving hot air stream (20-30 m/s) in which the drying process occurs. The dried solids are separated from the gases in a cyclone. Sometimes a bag filter is used for final cleaning of the gas stream before exhausting into atmosphere. High inlet gas temperatures are used because exposure time is short and the material remains at wet bulb temperature due to rapid evaporation of water. Flash dryers can handle maximum about 70% moisture content. Due to the low residence time the desired final moisture content is not reached. For this reason and for product transport reasons a part of the dried product is again transported through the dryer, see figure 283.

These dryers can not handle large particles and pasty materials. If the material to be dried can tolerate combustion products in the hot gas the air heater is usually of the direct fired type. Heat needed for water evaporation is about 4-4.2 MJ per kg water. These dryers are in general cheap. The most important criteria for air heating are:
- to be heated air mass flow is constant;
- only fresh air is heated, there is no recirculation;
- air must be heated to a temperature up to about 550 °C;
- in most cases very clean combustion is needed;
- capacity range is about 500 kW to 11 000 kW.

Burner selection
Since fresh air should be heated at a constant amount line burners without combustion air supply should be applied (see pages 139 ). If very clean and low NOx combustion is required the low NOx burners for air heating described in chapter IX must be applied.

Spray dryers
Figure 284 shows a typical spray dryer. A spray dryer is a sort of modified flash dryer. The feed is atomized before being introduced into the air stream. The part of the duct where the feed is introduced is enlarged. This gives the atomized particles time to dry before they contact the chamber walls, thus minimizing Sticking.
Spray dryers provide a longer residence time (3 to 10 s) to the particles during drying. This permits complete drying at reduced temperature. For this reason moisture content can exceed 80%.

Normal operating temperatures are between 180 and 250 °C. Capacities are ranging from 100 kW to 6000 kW. Heat needed for evaporation is about 4-4.2 MJ per kg water evaporated. If the material to be dried can tolerate combustion products in the hot gas the air heater is usually of the direct type (see also in this chapter article about the use of low NOx burners for spray drying milk powder).

The most important criteria for air heating are:
- the to be heated air mass flow is constant;
- only fresh air is heated, there is no recirculation;
- air must be heated to a temperature of about 250 °C;
- in most cases very clean combustion is needed;
- capacity range is about 100 kW to 6000 kW.

Burner selection
Since fresh air should be heated at a constant amount line burners without combustion air supply should be applied (see pages. {xxx}). If very clean and low NOx combustion is required the low NOx burners for air heating described in chapter IX must be applied.

Fluid bed dryers

Figure 285 shows a continuous fluid bed type dryer.
The word "fluid" is used here, meaning that fluidized solids exhibit many of the properties of a liquid. Fluidization can be defined as the suspension and agitation of a bed of particulate solids by a vertically rising stream of gas. Each particle is surrounded by the gas. The pressure drop of the gases flowing up through a fluidized bed is greater than the pressure drop of gases moving through a flash dryer. For this reason the location of the fan is at the gas inlet to the system, whereas the fan at a flash dryer is mounted at the gas outlet. Figure 285 shows a typical fluid bed dryer. The fluidizing gas is heated to 500 °C. The distributor plate supports the material and uniformly distributes the air across the cross section of the dryer. Gas temperature at the bottom of the distributor plate is 500 °C and on the top 90 °C. This temperature drop takes place in a distance of 10-15 cm. Fluid bed dryers are applied for granular materials. Design of fluid bed dryers is still very much an art based upon empirical knowledge. Typically applied gas velocities for fluidizing product having particle densities between 1000 and 2000 kg/m³ are given below.

<table>
<thead>
<tr>
<th>Average particle size (µm)</th>
<th>Velocity m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 - 300</td>
<td>0.2 - 0.4</td>
</tr>
<tr>
<td>300 - 800</td>
<td>0.4 - 0.8</td>
</tr>
<tr>
<td>800 - 2000</td>
<td>0.8 - 1.2</td>
</tr>
<tr>
<td>2000 - 5000</td>
<td>1.2 - 3.0</td>
</tr>
</tbody>
</table>

Many types of fluid bed dryers have been developed such as vibrated fluid beds, spouted beds and fluid bed granulators among many others. The most important criteria for air heating are the same as described for flash drying due to which the same type of burners can be applied.

Continuous tunnel and conveyor dryers

Tray, truck, tunnel and continuous conveyor dryers comprise a class of equipment that has two major characteristics, gentle handling of the product and the use of heated air passing through, or over, or impinging upon a bed of the product to be dried. The heated air both transfers heat to the product and carries moisture away from it.

In tray, truck, tunnel and conveyor dryers (see figure 286) the product is in a fixed or slowly moving bed with cross or through circulation of air ranging in velocities of 0.4 m/s in a multi conveyor dryer to 2 m/s in a tunnel dryer.
Tray and truck dryers are batch type dryers, see figure 286, whereas a tunnel truck dryer has some of the characteristics of a batch dryer but offers a semi continuous product flow. Typical temperatures are 70 to 210 °C. A tunnel truck dryer is so arranged that trucks are pulled or pushed through a tunnel (see figure 288).

In the shown tunnel truck dryer the hottest air is delivered at the dryest end of the product producing this way the best drying conditions (counter flow). Initial drying is gentle, with lower temperatures and higher moisture contents. Counter flow circulation is much used for fruit drying with high volume shrinkage; concurrent flow is used for applications requiring rapid initial drying followed by slow final drying.

Combinations of flow types are sometimes also applied. Side to side flow as shown in figure 287 is also possible in a tunnel dryer. This type of construction permits zoning of temperature, air flow and humidity along the direction of product flow.

Figure 289 shows a cutaway view of a typical conveyor dryer.

Conveyor sizes range of 0,6 to 4,5 m width and 3 to 60 m length. Through circulation air velocities range of 0,3 to 3 m/s giving static pressure losses between 0,025 to 20 mbar. The air temperatures are in range of 50 to 350 °C and most common 150 @C. Figure 290 shows a typical conveyor dryer arrangement.

The single conveyor arrangement is mostly used. Air flow is from a turbine fan through a perforated air distribution plate, through the bed of material (either air up or air down) and back to the fan. Reheating of the returning air may be through a steam coil or direct by injection of products of combustion from a gas burner.

Staging in a multiple conveyor dryer is employed when a large amount of product shrinkage occurs during early drying (e.g. in onions): dumping and reloading to a deeper bed increases efficiency. These dryers are used when slow, gentle drying with low velocities and moderate temperatures are desired.

An important special class of conveyor dryer is the impingement dryer (also called web dryer) with air circulation configuration as shown in figure 292 and figure 251 in the part of this book about incinerators.
Heated air is fed from a plenum to distribution nozzles from which it impinges upon the product at relatively high velocities ranging of 5 to mostly 25 m/s but in special dryers to 125 m/s. Applications include drying of fabrics coated paper etc. Temperatures of the supply air may range between 120 and 200 °C and in some applications even 450 °C.

**Energy and air heating considerations**

Typical heat load partition of a continuous conveyor dryer is given below.

- **Evaporation**: 55%
- **Material and product heating**: 12%
- **Make-up air heating**: 28%
- **Product entry / exit losses**: 3%
- **Radiation/convection losses**: 2%

Above shows what can be achieved in a good designed dryer. Evaporation heat load can be diminished by better mechanical dewatering, material and product heat up load can be reduced by conserving heat already in the product from upstream processes. In some dryers the exhaust can be diminished by using less make-up air and/or burners with closer stoichiometric combustion air control. By having less exhaust also the make-up air mass flow stream can be lowered. Better seal design and careful adjustment of inlet and outlet openings can lower heat losses. Better insulation panels will also reduce convection losses.

Heat recovery from exhaust air to preheat make-up air will also lower energy consumption. With these heat exchangers 50-70% of the available sensible heat can be recovered.

If the product tolerates the use of combustion gases in the drying air direct heating with gas burners can be applied. Direct gas firing with natural gas offers maximum flexibility and quickest response at least investment and fuel costs.

The selection of the proper burner system is however very important. We will try to give a short burner selection for many practical situations in recirculating drying processes.

**Situation 1**: To be heated air mass flow is constant and oxygen percentage is higher than 18%.

Burner selection.
For this situation line burners without combustion air supply (see figure 161) can be applied. These burners can also handle high back pressure differences which may occur during starting up of the dryer.

**Situation 2**: To be heated air mass flow has a high absolute humidity.

Burner selection.
For reasons that ignition and burner safeguarding cables and connections may get wet, on duct mounted burners should be applied (outside the duct mounted burners). These burners are in all cases burners with complete combustion air supply which may be line or forward flame burners (see figure 183). These burners are not sensitive to mass flow changes and moderate back pressure changes. Disadvantage of these burners might be that too much make-up air can be delivered into the drying process along with the combustion air for the burner.
Figure 293: Recirculating drying process provided on duct mounted line or forward flame burner

**Situation 3:** The air to be heated should be heated very evenly (no temperature differences).

**Burner selection.**
Line burners will give better heat supply distributions than forward flame burners. Line burners with profile plating are giving better mixing of combustion products with air to be heated than line burners without profile plating. The described special burner for air heating in which a heat resistant distribution pipe is applied (see figure 190) is for most application the best solution if good mixing is required (see figure 294).

Figure 294: Recirculating drying process provided with hot air supply through distribution pipe

**Situation 4:** Very clean combustion is required and low NOx levels are a must.

**Burner selection.**
For many food drying applications for human consumption a less than 1 ppm NOx level of the drying air is required. For these type of applications the described low NOx burners should be applied. A special section in this book handles about low NOx applications for spray drying of milk powder and vegetable drying.

**Situation 5:** Make-up air supply to the drying process should be as low as possible.

**Burner selection.**
If make-up air supply through the burner should be as low as possible, line burners without combustion air supply can be selected if the air to be heated contains 18 or more percent of oxygen. If there is less than 18% oxygen stoichiometric type line or forward flame burners may be applied. If the back pressure is constant also line burners fed with a stoichiometric gas/air mixture as described in chapter III can be applied.

**Situation 6:** Low NOx is required together with good mixing properties.

**Burner selection.**
For this application a low NOx line burner should be selected.

Combinations of above-mentioned 6 situations might be required. If in the case of situation 6 a good low NOx line burner is not available mixing plates or baffles should be added to improve mixing, see figure 295.

Figure 295: Ring and disc baffles

Furnaces and ovens

In this part furnace and oven applications are briefly described in which gas burners are very often applied. Some processes of the following industrial branches will be discussed:

- **steel industry:** reheat furnaces, annealing, tempering, galvanizing;
- **aluminium melting:**
- **pottery industry.**
Steel industry

The processes we will describe here are often called secondary finishing processes. After the slab, bloom or billet had been produced in a primary mill it is generally allowed to cool to room temperature and is then sent for secondary finishing either in the same works or elsewhere. Only a small amount of semi finished steel does not undergo secondary finishing and is sold directly.

Secondary finishing involves the production of steel plate, coil, bars or sections by passing semi finished steel through a secondary rolling mill. This always involves first reheating the steel and sometimes, as in the case of hot rolled strip, pickling the product to remove the scale produced in the heating and rolling processes.

After the secondary mill, steel may be sold directly or may pass on to a wide variety of further finishing processes such as cold rolling and annealing, plating and coating or drawing.

Reheat furnaces

Reheat furnaces heat the steel to around 1150-1,350 °C before it is passed through secondary rolling mills. A wide variety of continuous reheat furnaces is used. The most common type in integrated steel works is the pusher type, in which slabs or blooms are pushed through the furnace on insulated, water cooled rails known as skids. Walking beam furnaces are also used, particularly for billet and bloom reheating, in which case heating to 15 °C may suffice. Reheat furnaces are oil- or gas-fired, although sometimes in integrated steel works enriched BF gas is used. Most furnaces have recuperators, which achieve air preheats of 200-500 °C. Exhaust gases at 800-1200 °C are diluted with air before passing to the recuperator. The gases are clean but may contain SO\(_2\) if the furnace is oil-fired and if coke oven gas is used to enrich the BF gas.

Waste gases are discharged from reheating furnaces at lower temperatures than from soaking pits. However, more steel is heated in a reheating furnace and the heating requirement is greater; thus the potential for waste heat recovery is greater overall. There may also be a considerable amount of water cooling in the structure supporting the stock. There is an escape of waste gas into the atmosphere from the entrance to the furnace although attempts are made to minimise this loss by balancing the pressure in the furnace and by improving the fitting of the doors. The size of reheat furnaces varies considerably across the industry. In large integrated works they operate at 100-250 tons per hour while in some works they can be as small as a few tons per hour.

Energy use in reheating furnaces was estimated to be 2.4 GJ per ton of product. This specific energy consumption (SEC) was an average value calculated from the tonnages going through the various production routes such as hot strip, plate, heavy section, light section, rod and bar mills of the industry in 1978. The SEC range was 2.0-3.0 GJ per ton. In this context it is worth noting that a modern billet reheating furnace uses about 1.6-1.8 GJ per ton or even less.

It is important to realise that furnace design and operating conditions play an important role in the level of waste heat available. The SEC can be affected by delays in operation, poor insulation or water cooled structures, air ingress or combustion gas escape. These latter two parameters will depend on the pressure control of the furnace and the fitting of doors. It is still possible, however, to produce a meaningful Sankey diagram of energy flows for such a furnace using idealised energy values. Such a diagram is shown in figure 296.
Heat recovery and burner selection

Exhaust gases from steel reheat furnaces are a large single source of waste heat. Various types of recuperators are a standard fitment but there are considerable variations in their efficiency. The gases are clean and there are no serious technical problems in recovering heat from them. Air preheating is the basic use for the recovered heat but waste heat boilers can also be used where there is a demand for steam. In batch processes preheating of the prepared charge is a third possibility. Improved control of air/fuel ratio can considerably reduce the waste heat losses. Figure 297 shows a schematic in which burner placement can be seen.

In the shown furnace 12 self recuperative burners with a capacity each of 500 kW are mounted (Stordy). Many of the pusher type reheating furnaces are like the type shown in figure 298.
In these types of furnaces medium or low velocity burners are normally applied. Exhaust gases of these furnaces are around 800-900 °C. These gases are often cooled in a heat exchanger to preheat combustion air for the burner to 500-600 °C. Recuperative burners cannot be applied here because the combustion gases are flowing in counter flow to the product and are leaving the furnace at one end. Burners designed to be fed with hot combustion air were described in figure 299.

Figure 299 shows a small pusher type furnace. Sometimes flat-flame burners are applied in these furnaces. These burners are then situated in the furnace ceiling. At the end some tunnel burners are often mounted to seal the outlet opening with hot combustion products.

Figure 300 shows a very common car bottom furnace for stress relieving, heating before forging, heat treating, carburizing in boxes, annealing etc.

The shown furnace is a batch type furnace. A continuous furnace may have a similar construction with cars moving behind each other.
In some of the more high temperature car bottom furnaces the car support and the wheels may be heated up to 450 °C. Figure 301 shows how the edges of a car can be sealed with sandpockets. Figure 302 gives some other general constructions of small furnaces.

![Figure 301](image)

**Figure 301**

**Annealing furnaces**

When stock material, e.g. hot rolled coil, is cold rolled to produce strip, the steel becomes work hardened and requires high temperature annealing at 680-700 °C or higher to restore its optimum properties. Other products, such as billets, bars and plate also undergo annealing. For stainless annealing temperatures are 1050 °C. Present practice is to anneal coils of steel in batch furnaces or in continuous strip annealing furnaces using mainly natural gas.
In batch annealing a lift off furnace is lowered over a single coil or a stack of coils, for this reason often called stack annealers. These coils are first surrounded by a stainless steel cover or hood. The inner space is filled with a protective gas (mixture of nitrogen and hydrogen). Gas burners heat the annular space between the inner cover and the outer furnace structure. An annealing cycle will take several hours with controlled periods at specific temperatures. The energy consumption of these furnaces has been reported as 0.4 GJ per ton steel. Continuous furnaces using regenerative burners have losses of about 0.3 GJ per ton.

Figure 303 shows a typical stack annealing furnace in which the hood over the product and the recirculating fan can be seen. The shown furnace is heated with radiant tubes which is not often the case because the product is already guarded by the hood.

Figure 303: Stack annealing furnace with hood and radiant burners

Figure 304 shows the application of a tunnel burner for direct heating of the area around the muffle or the hood.
In more modern furnaces sometimes flat-flame burners were applied like the Stordy wall hugger burner. Today in most stacked annealing furnaces high velocity type burners are applied. Two types of stacked furnaces can be distinguished, the single stack and the multiple stack annealing furnace shown in figure 305.

As mentioned product temperature will be between 680 and 700 °C. The furnace temperature outside the muffle or hood will be about 800 °C at the start and will slowly be lowered to about 700 °C. In the most modern type furnaces regenerative high velocity burners are applied. Recuperative high velocity burners can not be made economical here due to the rather low exhaust temperature.

Aluminium melting

The primary melting process to produce aluminium from bauxite uses an extremely energy intensive electrolysis method which will not further be discussed here. The secondary refining process will however be discussed. The secondary aluminium industry's raw materials include clean scrap generated by semis and castings producers, old scrap generated from consumer goods at the end of their useful life (e.g. aircraft, cars, window frames, packaging), swarf and dross. The industry segregates the scrap according to its alloy constituents and blends it to produce ingots, mainly for the foundry industry. Primary ingot and alloying elements are added as necessary to produce the required specification.
Secondary refining is a batch operation. The blended materials are melted, usually in rotary or reverberatory furnaces.

The design of a typical reverberatory furnace is shown in figure 306. The metal is contained in a shallow hearth within a steel cased refractory box, usually of rectangular shape, with a stack at one end and oil- or gas-fired burners firing horizontally at the other end. The combustion space is large and a sliding door permits the easy charging of bulky pieces of metal. Smaller doors give access for stirring the metal, removing dross and fluxes and cleaning the refractory walls. Rotary furnaces are somewhat similar in design, except that the fixed rectangular box is replaced by a horizontal drum rotating slowly about its principal axis.

Heat is supplied via one or more oil or gas burner. Once molten, the metal is modified to the correct specification by adding more scrap, alloying elements or primary ingot. The temperature of the molten metal depends on its composition, but is commonly 700-750 °C - pure aluminium melts at 660 °C.

The temperature of the exhaust gases depends largely on how much air is allowed to enter the furnace and the stack. The temperature can be as high as 1,000 °C. The wide range in temperature reflects the variations in operating practice within the secondary refining sector. Specific energy consumptions reported were between 5 GJ and 10 GJ per ton. In very modern furnaces consumption values were reported as low as 3-4 GJ/ton.

The use of heat recovery equipment in the exhaust of these furnaces is difficult if dirty scrap is melted. Contaminants in the exhaust will then block or corrode the heat recovery equipment.

If however the problem of the fouling could be resolved, there would be considerable possibilities for preheating combustion air. Some test installations are now running with regenerative burners (see figures 269 and 307). These burners will save an estimated 40 percent of energy input. In the most modern of these types of furnaces medium velocity type burners are applied.
Figure 307: Reverberatory melter with regenerative burners

Figure 308 shows a by British Gas developed furnace to melt aluminium called immersed crucible furnace.

Figure 308: Immersed crucible aluminium melting furnace

In the aluminium industry many crucible furnaces are applied as shown in the sketch from figure 309.
Figure 309: Crucible aluminium melting furnace

In modern furnaces high velocity burners are applied. On larger crucible furnaces a recuperator is applied on the exhaust to preheat combustion air for the burner. Also recuperative burners are sometimes applied. Figure 310 shows a crucible furnace installation with built in recuperative system.

Figure 310: Crucible furnace with built in recuperator

Another application often seen, not only in the aluminium industry is ladle heating. Figure 311 shows the complete burner installation with combustion air fan for heating the ladle. For these applications high velocity burners are applied. If one ladle is heated another ladle should follow. For this reason most of these installations are limited transportable (see figure 312).

Figure 311: Burner installation for ladle heating (Stordy)
Hot dip galvanizing (bath process)

The process
The hot dip galvanizing process produces a durable, abrasion resistant coating of metallic zinc and zinc-iron layers metallurgically bonded to the steel base and completely covering of the work piece.

Hot dip galvanizing prevents corrosion of steel by:

a) providing a tough, durable barrier coating of metallic zinc which completely seals the steel from corrosive environments;
b) cathodic or sacrificial protection.

Before the work or material can be hot dip galvanized, it should be carefully cleaned from rust, oil, paint and other surface contaminants. For this purpose the material first passes a number of baths after which the hot dip galvanizing follows (see figure 313).

The pickling stage is done in a bath filled with 15% HCl concentration in water or with 20% H2SO4 in water. The last type of baths should have a temperature of about 40 °C. The fluxbath contains usually 30% zinc ammonium chloride with wetting agents, heated to about 65 °C. The flux solution dissolves and absorbs any remaining impurities. It also improves the creeping of the zinc layer.

The material is then carefully dried at a temperature of about 130 °C to evaporate all remaining water to prevent any splashing of the zinc bath. The material is then immersed in the galvanizing bath. In this bath the steel surface is wetted by the melted zinc and reacts to form zinc-iron alloy layers. To allow formation of the galvanized coating, the work remains in the bath until its temperature reaches that of the melted zinc, in the range 445 °C to 465 °C. The period of immersion varies from a few seconds for continuously galvanized sheet steel to several minutes.
for massive steel structural members. The thickness of the zinc layer with hot dip galvanizing will be between 40 and about 120 microns (300 grams zinc/m² at 40 microns). The thickness of the zinc layer depends upon the next factors:
a) the temperature of the zinc bath. However, this temperature can never be higher than 465 °C;
b) the zinc bath composition;
c) the remaining time of the material in the bath;
d) the composition of the material, e.g. silicon in the material will give thicker layers.

The galvanizing bath
A typical galvanizing tank is shown in figure 314.

Figure 314

These tanks are often 6,5 m long because standard material sizes are 6 m. The tanks are made of special steel (Armco steel or plate with low carbon and low silicon). The wall thickness is 50 mm. The zinc is melted in the tank. The melting point of the zinc is 418 °C. The temperature of the bath will be held on about 450 °C. After the zinc is melted, the zinc will be staying melted in the tank for 5 or more years or as long as the lifetime of the tank. Make-up zinc will be added in accordance to the zinc consumption. As mentioned the maximum bath temperature is 465 °C. At 470 °C or higher there will be a rapid reaction between the zinc and the iron bath wall due to which the wall thickness of the tank will decrease very rapidly. The maximum practical temperature of about 465 °C is a very important design data for selecting burners for heating the tank because it should be avoided that at any place the tank will reach a too high temperature. A practical figure for heat supply from the outside wall to avoid overheating is 40 000 kcal/m²/h or 47 kW/m². The surface radiation loss is about 57 000 kJ/m²/h (66 kW). The heat needed per kg of iron is 280 kJ. Zinc make-up estimated is often at 10% of the work handled. 1 kg of make-up zinc needs 315 kJ. With mentioned heat supply per m² the heat losses of the bath, caused by zinc surface radiation heat losses and losses for heating the material, can be covered. Figure 315 shows an installation with flat-flame burners. Flat-flame burners were selected to obtain even energy supply to the tank wall. In most cases flat-flame burners with a maximum capacity of 115 kW at about 1,5 m from each other are selected. Another approach often found is tank heating with hot (1000 °C) air, shown in figure 316. Very often also high velocity burners (two per long tank side@ are applied for zinc tank heating.
Sometimes a tank made out of refractory material is applied as shown in figure 318. The advantage of this tank construction is the much longer lifetime of the tank giving the possibility to work with higher zinc temperatures than the mentioned 465 °C. The disadvantage is the much larger zinc bath volume due to which constantly more zinc in the bath is needed (dead capital loss).

These types of baths are heated with burners - giving reverberatory heat from the ceiling. Normally high velocity type tunnel burners can be selected here.
Continuous hot dip galvanizing (sendzimir process)

Figure 320 shows a typical arrangement of a continuous galvanizing line. The installation consists of an about 8 m long preheat furnace for preheating and flame cleaning of the incoming strip by direct fired high velocity burners. The reheat furnace is followed by a controlled atmosphere heating section (about 15 long) in which gas-fired radiant tubes are applied. After these two sections a controlled cool and a final cool section is built in the line.

The preheat section is supplied with a number of recuperative high velocity burners. The preheat section will in general operate at approx. 1250 °C. In this section the burners are placed just below and above the plate to provide what is called a sweeping-effect. The burners are adjusted on about 20% excess gas. The installation was equipped with recuperative burners shown in figure 319. The selected burners had a capacity of 170 kW each.

The burners are controlled "high-low-off" through gas and air solenoid valves mounted on the burner, in conjunction with the temperature control system of the heating zones.

The waste products of combustion are drawn through each burner by inductors thereby preheating the combustion air.

The plate is heated in this section to about 600 °C.

The controlled atmosphere section in which H2 and N2 gases are supplied is provided with about 200 radiant tube burners (See figure 319). These burners are described before.

This section is divided in a number of controlled zones; in addition, each zone is divided in groups of approx. 8 radiant tubes. The temperature in each control zone (approx. 800-900 °C) is controlled through a thermocouple in the zone and a temperature controller, whereas each group of radiant
tubes within a zone is controlled "on-off" in a sequence manner through a burner sequence controller.

In this section the plate is heated to 850-900 °C.
In the cooling sections the plate will be cooled to about 470 °C before it is transported through the galvanizing tank (460 °C).
The radiant tube burner is controlled "on-off" through air and gas solenoid valves on each burner. Each burner is fitted with direct spark ignition at the burner nozzle and UV-type flame supervision.

figure 320: Continuous galvanizing line (Thermtec)

Annealing furnace and pickling line for stainless steel strip

The furnace section in a stainless steel A&P line generally consists of one or more catenary type heating chambers for heating the strip to 1060-1120 °C, see figure 321.
The furnace consists of two heating chambers equipped with a total of 84 recuperative high velocity burners.
Each heating chamber is divided in a number of control zones and the temperature in each control zone is controlled through a thermocouple in the zone and a temperature controller.
The burners in the zones are controlled in a proportioning manner through zone gas and air control valves.
The products of combustion from the burners are exhausted through a centralized suction type exhaust system, incorporating also an economizer to further use the heat in the flue products by heating plant water. The recuperative burners applied in this furnace (see figure 324) have a rating of max. 200 kW each and are equipped with direct spark ignition and UV flame supervision.
The air/gas combustion ratio of the burners in a zone can be adjusted in a wide range to suit the conditions required for the products being treated in this furnace. In most cases they are working with 20-50% excess air.
The degree of return flow of combustion products over the burner recuperators is controlled by special microprocessor type control equipment as a function of burner power and temperature.

Figure 321: Annealing furnace and pickling line for stainless steel (Thermtec)

Bright anneal line for stainless steel

A typical bright anneal furnace for stainless steel is a vertical muffle furnace, in which the strip being heated is isolated from the burner products of combustion by means of a heat-resistant alloy muffle tube is shown in figure 322.
The heating chamber of this furnace is equipped with recuperative burners, see figure 324, divided in a number of control zones. The temperature in each control zone (up to approx. 1150 °C) is controlled through a thermocouple in the zone and a temperature controller, whereas the burners within a zone are controlled on-off in a sequential manner through a burner sequence controller. The products of combustion from the burners are exhausted by means of an air-eductor on each burner.

The recuperative burners used in this furnace have a rating of max. 150 kW and are equipped with air and gas solenoid valves, direct spark ignition and UV flame supervision. The application of these burners in this furnace has resulted in a relative fuel saving of approx. 35% as compared to the previous proportionally controlled cold air burners. Further, a significant increase in production capacity has been obtained due to better temperature uniformity on the muffle and an increased heat transfer co-efficient.
Pottery industry

The pottery industry can be divided into sectors covering a number of main types of products as shown below.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Some of the products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table ware</td>
<td>porcelain, china, Stone ware</td>
</tr>
<tr>
<td>Sanitary ware</td>
<td>closet pots etc.</td>
</tr>
<tr>
<td>Tiles</td>
<td>wall tiles, floor tiles</td>
</tr>
<tr>
<td>Electrical ceramics</td>
<td>insulators for high and low voltages</td>
</tr>
</tbody>
</table>

The manufacturing processes vary for different products but have broad similarities across the industry. They consists of crushing and blending the raw materials - including china clay, bone ash, feldspar, quartz and ball clay - required for the particular product, then mixing them with water to form a suspension known as slip. After further treatment of the slip, ware is formed either by plastic moulding, dust pressing or slip casting. The moulded articles are then dried before firing.

The drying consumes a lot of energy, about 25% of the total energy consumption of this industry. Main energy sources for drying include gas burners, steam of hot oil filled radiator systems and also hot air from exhaust gases of adjacent kilns.

Firing of the ware is carried out in a variety of kilns, either continuous (tunnel type) or batch type. The firing operation takes place at temperatures of 1100-1250 °C.

Tunnel kilns

Ware is stacked on trucks which pass through the tunnel kiln, taking about 20 to 90 hours through the warming up, firing and cooling stages. Figure 325 shows a schematic layout of a tunnel kiln.
These kilns are constructed essentially of insulating brickwork and are up to 100 m long and 3-4 m wide. Air is blown in at one end to cool the hot, fired ware directly and is heated in the process before mixing with the burner flames in the firing zone. The air serves as secondary combustion air in the firing zone. The cold incoming ware is preheated by the hot exhaust gases from the firing zone.

There are two main types of tunnel kilns, the direct fired kilns where the flame comes into contact with the product and the muffle kilns where the flame is separated from the ware by a thin refractory wall. Most kilns are direct fired and more efficient than the muffle kilns (30-50% more efficient). Combustion air for the burners is often preheated by passing it through passageways between the brickwork walls of the cooling zone.

The exhaust gas temperature at the base of the kilns is in general between 140 and 200 °C. About 20 to 25% of the energy is lost in the form of waste gases. This air may be used for drying purposes.

**Batch type production**

A very large number of batch type production kilns is in use. In these batch type kilns the ware is stacked in the kiln or on cars which are pushed into it. The ware is heated at a controlled rate up to the maximum temperature of firing, held for the specified period, then cooled usually by opening first the dampers and finally the kiln doors and allowing the natural draught to draw air through the kiln. Cycle times vary with the product and are between 8 and 24 hours. Gas fired kilns may be of the box type or portable cover type. Figure 326 shows a typical portable cover kiln or also called shuttle kiln.
This kiln is fired by vertical tunnel type burner along the side walls and flueing centrally through the perforated hearth. It is vital that each piece of ware has a similar thermal history in the furnace. Thus an essential feature of any satisfactory firing system is even temperature distribution. The use of high velocity burners is particularly useful in providing temperature uniformity in pottery kilns. The ware in pottery kilns is normally loaded in such a way that central pieces are shaded from direct radiation. For these pieces the influence of high velocity burning is important. Compared with continuous kilns, in which extensive load preheating is carried out, intermittent kilns are inefficient unless air recuperation is practised. For this reason modern kilns are using recuperative high velocity burners. Figure 327 shows a single truck intermittent kiln with high velocity recuperative burner.

![Figure 327](image)

On these types of truck kilns a single 290 kW recuperative high velocity burner is applied to heat 4.5 m³ of space instead of two banks of four tunnel burners with a total capacity of 480 kW. In general with high velocity recuperative burners a fuel saving can be obtained of about 30%. It will also be understood that the investment of one high velocity recuperative burner can be lower than for 8 tunnel type burners.
REFERENCES

(omitted)

DESCRIBED AND MENTIONED APPLICATIONS

(omitted)