CHAPTER 44
COMBUSTION

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44.1 FUNDAMENTALS OF COMBUSTION

44.1.1 Air–Fuel Ratios

Combustion is rapid oxidation, usually for the purpose of changing chemical energy into thermal energy—heat. This energy usually comes from oxidation of carbon, hydrogen, sulfur, or compounds containing C, H, and/or S. The oxidant is usually O_2—molecular oxygen from the air.

The stoichiometry of basic chemical equation balancing permits determination of the air required to burn a fuel. For example,

$$1CH_4 + 2O_2 \rightarrow 1CO_2 + 2H_2O$$

where the units are moles or volumes; therefore, 1 ft^3 of methane (CH_4) produces 1 ft^3 of CO_2; or 1000 m^3 CH_4 requires 2000 m^3 O_2 and produces 2000 m^3 H_2O. Knowing that the atomic weight of C is 12, H is 1, N is 14, O is 16, and S is 32, it is possible to use the balanced chemical equation to predict weight flow rates: 16 lb/hr CH_4 requires 64 lb/hr O_2 to burn to 44 lb/hr CO_2 and 36 lb/hr H_2O.

If the oxygen for combustion comes from air, it is necessary to know that air is 20.99% O_2 by volume and 23.20% O_2 by weight, most of the remainder being nitrogen.

It is convenient to remember the following ratios:

$$\text{air}/O_2 = 100/20.99 = 4.76 \text{ by volume}$$
$$N_2/O_2 = 3.76 \text{ by volume}$$
$$\text{air}/O_2 = 100/23.20 = 4.31 \text{ by weight}$$
$$N_2/O_2 = 3.31 \text{ by weight}$$

Rewriting the previous formula for combustion of methane,

$$1CH_4 + 2O_2 + 2(3.76)N_2 \rightarrow 1CO_2 + 2H_2O + 2(3.76)N_2$$

or

$$1CH_4 + 2(4.76)\text{air} \rightarrow 1CO_2 + 2H_2O + 2(3.76)N_2$$

Table 44.1 lists the amounts of air required for stoichiometric (quantitatively and chemically

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Table 44.1 Proper Combining Proportions for Perfect Combustion[a]

Fuel	vol O_2 / vol fuel	vol air / vol fuel	wt O_2 / wt fuel	wt air / wt fuel	ft^3O_2 / lb fuel	ft^3 air / lb fuel	m^2O_2 / kg fuel	m^3 air / kg fuel
Acetylene, C_2H_2	2.50	11.9	3.08	13.3	36.5	174	2.28	10.8
Benzene, C_6H_6	7.50	35.7	3.08	13.3	36.5	174	2.28	10.8
Butane, C_4H_{10}	6.50	31.0	3.59	15.5	42.5	203	2.65	12.6
Carbon, C	—	—	2.67	11.5	31.6	150	1.97	9.39
Carbon monoxide, CO	0.50	2.38	0.571	2.46	6.76	32.2	0.422	2.01
Ethane, C_2H_6	3.50	16.7	3.73	16.1	44.2	210	2.76	13.1
Hydrogen, H_2	0.50	2.38	8.00	34.5	94.7	451	5.92	28.2
Hydrogen sulfide, H_2S	1.50	7.15	1.41	6.08	16.7	79.5	1.04	4.97
Methane, CH_4	2.00	9.53	4.00	17.2	47.4	226	2.96	14.1
Naphthalene, $C_{10}H_8$	—	—	3.00	12.9	35.5	169	2.22	10.6
Octane, C_8H_{18}	—	—	3.51	15.1	41.6	198	2.60	12.4
Propane, C_3H_8	5.00	23.8	3.64	15.7	43.1	205	2.69	12.8
Propylene, C_3H_6	4.50	21.4	3.43	14.8	40.6	193	2.54	12.1
Sulfur, S	—	—	1.00	4.31	11.8	56.4	0.74	3.52

[a] Reproduced with permission from *Combustion Handbook.*[1] (See Ref. 1)

correct) combustion of a number of pure fuels, calculated by the above method. (Table 46.1*c* lists similar information for typical fuels that are mixtures of compounds, calculated by the above method, but weighted for the percentages of the various compounds in the fuels.)

The stoichiometrically correct (perfect, ideal) air/fuel ratio from the above formula is therefore 2 + 2(3.76) = 9.52 volumes of air per volume of the fuel gas. More than that is called a "lean" ratio, and includes excess air and produces an oxidizing atmosphere. For example, if the actual air/fuel ratio were 10:1, the %excess air would be

$$\frac{10 - 9.52}{9.52} \times 100 = 5.04\%$$

Communications problems sometimes occur because some people think in terms of air/fuel ratios, others in fuel/air ratios; some in weight ratios, others in volume ratios; and some in mixed metric units (such as normal cubic meters of air per metric tonne of coal), others in mixed American units (such as ft^3 air/gal of oil). To avoid such confusions, the following method from Ref. 1 is recommended.

It is more convenient to specify air/fuel ratio in unitless terms such as %air (%aeration), %excess air, %deficiency of air, or equivalence ratio. Those experienced in this field prefer to converse in terms of %excess air. The scientific community favors equivalence ratio. The %air is easiest to use and explain to newcomers to the field: "*100% air*" is the correct (stoichiometric) amount; 200% air is twice as much as necessary, or 100% excess air. *Equivalence ratio,* widely used in combustion research, is the actual amount of fuel expressed as a fraction percent of the stoichiometrically correct amount of fuel. The Greek letter phi, ϕ, is usually used: $\phi = 0.9$ is lean; $\phi = 1.1$ is rich; and $\phi = 1.0$ is "on-ratio."

Formulas relating %air, ϕ, %excess air (%XS), and %deficiency of air (%def) are

$$\%\text{air} = 100/\phi = \%\text{XS} + 100 = 100 - \%\text{def}$$

$$\phi = \frac{100}{\%\text{XS} + 100} = \frac{1}{1 - (\%\text{def}/100)}$$

$$\%\text{XS} = \%\text{air} - 100 = \frac{1 - \phi}{\phi} \times 100$$

$$\%\text{def} = 100 - \%\text{air} = \frac{\phi - 1}{\phi} \times 100$$

Table 44.2 lists a number of equivalent terms for convenience in converting values from one "language" to another.

Excess air is undesirable, because, like N_2, it passes through the combustion process without chemical reaction; yet it absorbs heat, which it carries out the flue. The percent available heat (best possible fuel efficiency) is highest with zero excess air. (See Fig. 44.1.)

Excess fuel is even more undesirable because it means there is a deficiency of air and some of the fuel cannot be burned. This results in formation of soot and smoke. The accumulation of unburned fuel or partially burned fuel can represent an explosion hazard.

Enriching the oxygen content of the combustion "air" above the normal 20.9% reduces the nitrogen and thereby reduces the loss due to heat carried up the stack. This also raises the flame temperature, improving heat transfer, especially that by radiation.

Vitiated air (containing less than the normal 20.9% oxygen) results in less fuel efficiency, and may result in flame instability. Vitiated air is sometimes encountered in incineration of fume streams or in staged combustion, or with flue gas recirculation.

44.1.2 Fuels

Fuels used in practical industrial combustion processes have such a major effect on the combustion that they must be studied simultaneously with combustion. Fuels are covered in detail in later chapters, so the treatment here is brief, relating only to the aspects having direct bearing on the combustion process.

Gaseous fuels are generally easier to burn, handle, and control than are liquid or solid fuels. Molecular mixing of a gaseous fuel with oxygen need not wait for vaporization nor mass transport within a solid. Burning rates are limited only by mixing rates and the kinetics of the combustion reactions; therefore, combustion can be compact and intense. Reaction times as short as 0.001 sec and combustion volumes from 10^4 to 10^7 Btu/hr · ft^3 are possible at atmospheric pressure.[2] Gases of low calorific value may require such large volumes of air that their combustion rates will be limited by the mixing time.

Combustion stability means that a flame lights easily and then burns steadily and reliably after the pilot (or direct spark) is programmed off. Combustion stability depends on burner geometry, plus

Table 44.2 Equivalent Ways to Express Fuel-to-Air or Air-to-Fuel Ratios[1]

	ϕ	%air	%def	%XS
Fuel rich	2.50	40	60	
(air lean)	1.67	60	40	
	1.25	80	20	
	1.11	90	10	
	1.05	95	5	
Stoichiometric	1.00	100	0	0
Fuel lean	0.95	105		5
(air rich)	0.91	110		10
	0.83	120		20
	0.78	130		30
	0.71	140		40
	0.62	160		60
	0.56	180		80
	0.50	200		100
	0.40	250		150
	0.33	300		200
	0.25	400		300
	0.20	500		400
	0.167	600		500
	0.091	1100		1000
	0.048	2100		2000

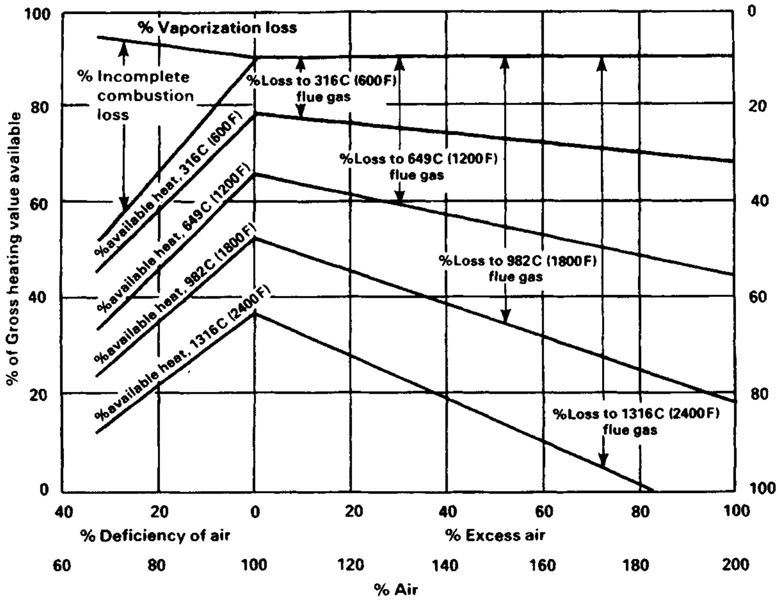

Fig. 44.1 Percent available heat (best possible efficiency) peaks at stoichiometric air/fuel ratio.[1]

air and fuel flow controls that maintain the point(s) of flame initiation (a) above the fuel's minimum ignition temperature, (b) within the fuel's flammability limits, and (c) with feed speed equal to flame speed—throughout the burner's full range of firing rates and conditions. (Fuel properties are discussed and tabulated in Chapters 46 and 47.)

Liquid fuels are usually not as easily burned, handled, or controlled as are gaseous fuels. Mixing with oxygen can occur only after the liquid fuel is evaporated; therefore, burning rates are limited by vaporization rates. In practice, combustion intensities are usually less with liquid fuels than with high calorific gaseous fuels such as natural gas.

Because vaporization is such an integral part of most liquid fuel burning processes, much of the emphasis in evaluating liquid fuel properties is on factors that relate to vaporization, including viscosity, which hinders good atomization, the primary method for enhancing vaporization. Much concern is also devoted to properties that affect storage and handling because, unlike gaseous fuels that usually come through a public utility's mains, liquid fuels must be stored and distributed by the user.

The stability properties (ignition temperature, flammability limits, and flame velocity) are not readily available for liquid fuels, but flame stability is often less critical with liquid fuels.

Solid fuels are frequently more difficult to burn, handle, and control than liquid or gaseous fuels. After initial volatilization, the combustion reaction rate depends on diffusion of oxygen into the remaining char particle, and the diffusion of carbon monoxide back to its surface, where it burns as a gas. Reaction rates are usually low and required combustion volumes high, even with pulverized solid fuels burned in suspension. Some fluidized bed and cyclone combustors have been reported to reach the intensities of gas and oil flames.[2]

Most commonly measured solid fuel properties apply to handling in stokers or pulverizers. See Chapter 48.

Wastes, by-product fuels, and gasified solids are being used more as fuel costs rise. Operations that produce such materials should attempt to consume them as energy sources. Handling problems, the lack of a steady supply, and pollution problems often complicate such fuel usage.

For the precise temperature control and uniformity required in many industrial heating processes, the burning of solids, especially the variable quality solids found in wastes, presents a critical problem. Such fuels are better left to very large combustion chambers, particularly boilers. When solids and wastes must be used as heat sources in small and accurate heating processes, a better approach is to convert them to low-Btu (producer) gas, which can be cleaned and then controlled more precisely.

44.2 PURPOSES OF COMBUSTION

The purposes of combustion, for the most part, center around elevating the temperature of something. This includes the first step in all successive combustion processes—the pilot flame—and, similarly, the initiation of incineration. Elevating the temperature of something can also make it capable of transmitting light or thermal energy (radiation and convection heat transfer), or it can cause chemical dissociation of molecules in the products of combustion to generate a special atmosphere gas for protection of materials in industrial heat processing.

All of the above functions of combustion are minor in comparison to the heating of air, water and steam, metals, nonmetallic minerals, and organics for industrial processing, and for space comfort conditioning. For all of these, it is necessary to have a workable method for evaluating the heat available from a combustion process.

Available heat is the heat accessible for the load (useful output) and to balance all losses other than stack losses. (See Fig. 44.2.) The available heat per unit of fuel is

$$\mathrm{AH} = \mathrm{HHV} - \text{total stack gas loss} = \mathrm{LHV} - \text{dry stack gas loss}$$

$$\%\ \text{available heat} = 100(\mathrm{AH}/\mathrm{HHV})$$

where AH = available heat, HHV = higher heating value, and LHV = lower heating value, as defined in Chapter 47. Figure 44.3 shows values of % available heat for a typical natural gas; Fig. 44.4 for a typical residual oil; and Fig. 53.2 in Chapter 53, for a typical distillate oil.

Example 44.1

A process furnace is to raise the heat content of 10,000 lb/hr of a load from 0 to 470 Btu/lb in a continuous furnace (no wall storage) with a flue gas exit temperature of 1400°F. The sum of wall loss and opening loss is 70,000 Btu/hr. There is no conveyor loss. Estimate the fuel consumption using 1000 Btu/ft^3 natural gas with 10% excess air.

Solution: From Fig. 44.3, % available heat = 58.5%. In other words, the flue losses are 100% − 58.5% = 41.5%. The sum of other losses and useful output = 70,000 + (10,000)(470) = 4,770,000 Btu/hr. This constitutes the "available heat" required. The required gross input is therefore 4,770,000/0.585 = 8,154,000 Btu/hr, of 8154 ft^3/hr of natural gas (and about 81.540 ft^3/hr of air).

The use of the above precalculated % available heats has proved to be a practical way to avoid long iterative methods for evaluating stack losses and what is therefore left for useful heat output

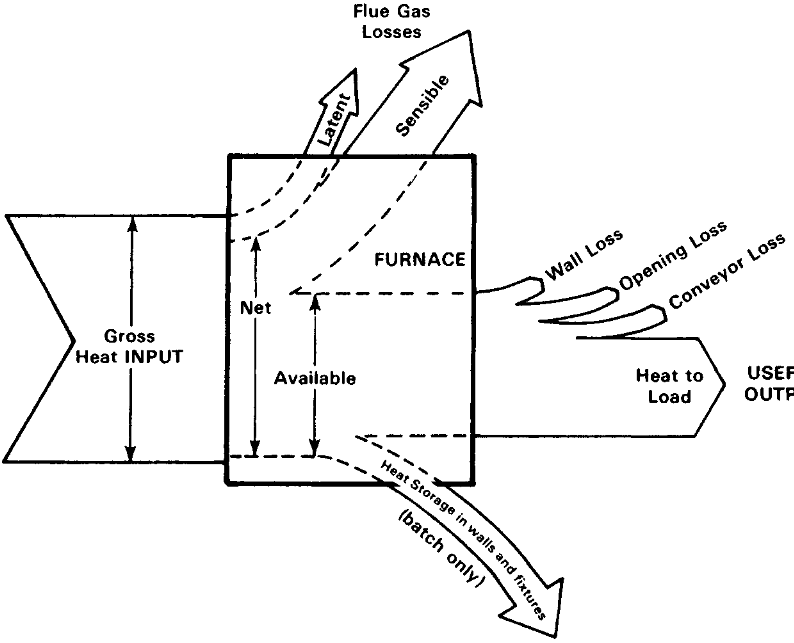

Fig. 44.2 Sankey diagram for a furnace, oven, kiln, incinerator, boiler, or heater—a qualitative and roughly quantitative method for analyzing efficiency of fuel-fired heating equipment.

and to balance other losses. For low exit gas temperatures such as encountered in boilers, ovens, and dryers, the dry stack gas loss can be estimated by assuming the total exit gas stream has the specific heat of nitrogen, which is usually a major component of the poc (products of combustion).

$$\frac{\text{dry stack loss}}{\text{unit of fuel}} = \left(\frac{\text{lb dry poc}}{\text{unit fuel}}\right)\left(\frac{0.253\ \text{Btu}}{\text{lb poc (°F)}}\right)(T_{\text{exit}} - T_{\text{in}})$$

or

$$\left(\frac{\text{scf dry proc}}{\text{unit fuel}}\right)\left(\frac{0.0187\ \text{Btu}}{\text{scf poc (°F)}}\right)(T_{\text{exit}} - T_{\text{in}})$$

For a gaseous fuel, the "unit fuel" is usually scf (standard cubic foot), where "standard" is at 29.92 in. Hg and 60°F or nm^3 (normal cubic meter), where "normal" is at 1.013 bar and 15°C.

Heat transferred from combustion takes two forms: radiation and convection. Both phenomena involve transfer to a surface.

Flame radiation comes from particle radiation and gas radiation. The visible yellow-orange light normally associated with a flame is actually from solid soot or char particles in the flame, and the "working" portion of this form of heat transfer is in the infrared wavelength range. Because oils have higher C/H ratios than gaseous fuels, oil flames are usually more yellow than gas flames (although oil flames can be made blue). Gas flames can be made yellow, by a delayed-mixing burner design, for the purpose of increasing their radiating capability.

Particulate radiation follows the Stefan-Boltzmann law for solids, but depends on the concentration of particles within the flame. Estimating or measuring the particle temperature and concentration is difficult.

Gas radiation and blue flame radiation contain more ultraviolet radiation and tend to be less intense. Triatomic gases (CO_2, H_2O, and SO_2) emit radiation that is largely invisible. Gases beyond the tips of both luminous and nonluminous flames continue to emit this gas radiation. As a very broad generalization, blue or nonluminous flames tend to be hotter, smaller, and less intense radiators than luminous flames. Gas radiation depends on the concentrations (or partial pressures) of the triatomic molecules and the beam thickness of their "cloud." Their temperatures are very transient.

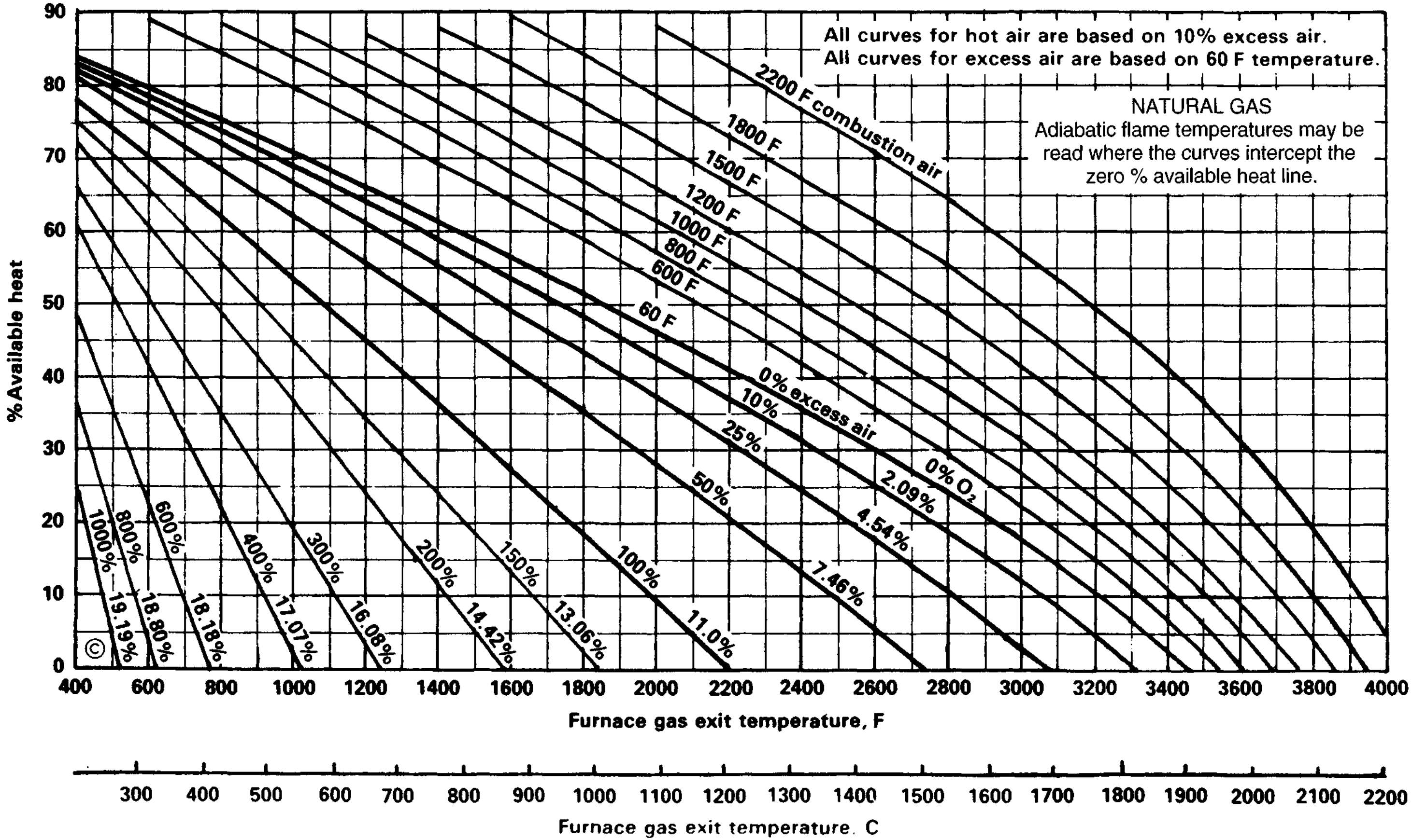

Fig. 44.3 Available heat for 1000 Btu/ft^3 natural gas. Examples: In a furnace with 1600°F flue temperature, 60°F air, and 10% excess air, read that 54% of the gross heat input is available for heating the load and balancing the losses other than stack losses; and, at the x-intercept, read that the adiabatic flame temperature will be 3310°F. If the combustion air were 1200°F instead of 60°F, read that the available heat would be 77% and that the adiabatic flame temperature would be 3760°F. It is enlightening to compare this graph with Fig. 44.16 for oxy-fuel firing and oxygen enrightment.

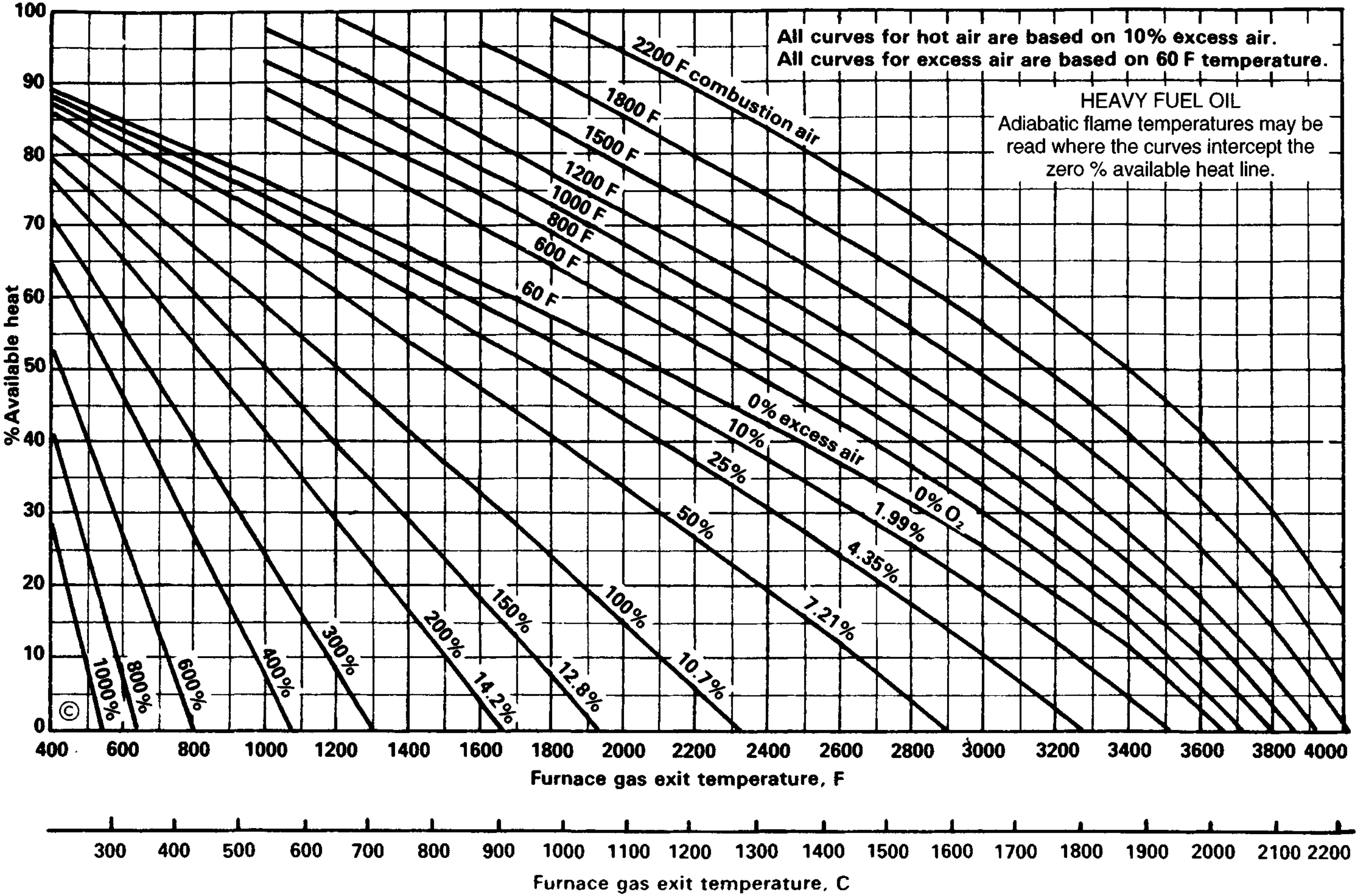

Fig. 44.4 Available heat for 153,120 gross Btu/gal residual fuel oil (heavy, No. 6). With 2200°F gases leaving a furnace, 1000°F air entering the burners, and 10% excess air, 62% of the 153,120 is available; 100% − 62% = 38% is stack loss.

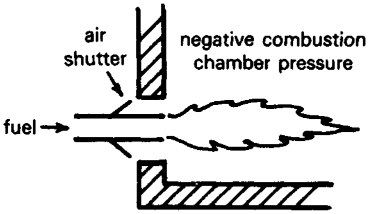

Fig. 44.5 Open, natural draft-type burner.

Convection from combustion produces beyond the flame tip follows conventional convection formulas—largely a function of velocity. This is the reason for recent emphasis on high-velocity burners. Flame convection by actual flame impingement is more difficult to evaluate because (a) flame temperatures change so rapidly and are so difficult to measure or predict, and (b) this involves extrapolating many convection formulas into ranges where good data are lacking.

Refractory radiation is a second stage of heat transfer. The refractory must first be heated by flame radiation and/or convection. A gas mantle, so-called "infrared" burners, and "radiation burners" use flame convection to heat some solid (refractory or metal) to incandescence so that they become good radiators.

44.3 BURNERS

In some cases, a burner may be nothing more than a nozzle. Some would say it includes a mixing device, windbox, fan, and controls. In some configurations, it is difficult to say where the burner ends and the combustion chamber or furnace begins. In this section, the broadest sense of the terms will generally be used.

A combustion system provides (1) fuel, (2) air, (3) mixing, (4) proportioning, (5) ignition, and (6) flame holding. In the strictest sense, a burner does only function 6; in the broadest sense, it may do any or all of these functions.

44.3.1 Burners for Gaseous Fuels

Open and natural draft-type burners rely on a negative pressure in the combustion chamber to pull in the air required for combustion, usually through adjustable shutters around the fuel nozzles. The suction in the chamber may be natural draft (chimney effect) or induced draft fans. A crude "burner" may be nothing more than a gas gun and/or atomizer inserted through a hole in the furnace wall. Fuel–air mixing may be poor, and fuel–air ratio control may be nonexistent. Retrofitting for addition of preheated combustion air is difficult. (See Fig. 44.5.)

Sealed-in and power burners have no intentional "free" air inlets around the burner, nor are there air inlets in the form of louvers in the combustion chamber wall. All air in-flow is controlled, usually by a forced draft blower or fan pushing the air through pipes or a windbox.

These burners usually have a higher air pressure drop at the burner, so air velocities are higher, enabling more through mixing and better control of flame geometry. Air flow can be measured, so automatic air–fuel ratio control is easy. (See Fig. 44.6.)

Windbox burners often consist of little more than a long atomizer and a gas gun or gas ring. These are popular for boilers and air heaters where economic reasons have dictated that the required large volumes of air be supplied at very low pressure (2–10 in. wc) (in. wc = inches of water column). Precautions are necessary to avoid fuel flowback into the windbox. (See Fig. 44.7.)

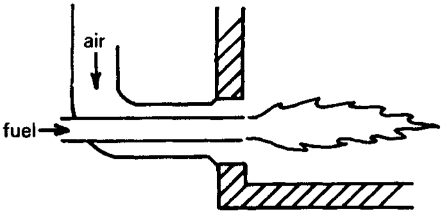

Fig. 44.6 Sealed-in, power burner.

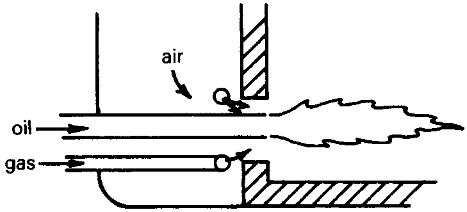

Fig. 44.7 Windbox burner.

Packaged burners usually consist of bolt-on arrangements with an integral fan and perhaps integral controls. These are widely used for new and retrofit installations from very small up to about 50 × 10^6 Btu/hr. (See Fig. 44.8.)

Premix burner systems may be found in any of the above configurations. Gas and air are thoroughly mixed upstream of the flame-holding nozzle. Most domestic appliances incorporate premixing, using some form of gas injector or inspirator (gas pressure inducing air through a venturi). Small industrial multiport burners of this type facilitate spreading a small amount of heat over a large area, as for heating kettles, vats, rolls, small boilers, moving webs, and low-temperature processing of conveyorized products. (See Fig. 44.9.) Large single port premix burners have been replaced by nozzle-mix burners. Better fuel–air ratio control is possible by use of aspirator mixers. (Air injection provides the energy to draw in the proper proportion of gas.) (See Fig. 44.10.) Many small units have undersized blowers, relying on furnace draft to provide secondary air. As fuel costs rise, the unwarranted excess air involved in such arrangements makes them uneconomical.

Larger than a 4-in. (100-mm) inside-diameter mixture manifold is usually considered too great an explosion risk. For this reason, mixing in a fan inlet is rarely used.

Nozzle-mix burner systems constitute the most common industrial gas burner arrangement today. Gas and air are mixed as they enter the combustion chamber through the flame holder. (See Fig. 44.11.) They permit a broad range of fuel–air ratios, a wide variety of flame shapes, and multifuel firing. A very wide range of operating conditions are now possible with stable flames, using nozzle-mix burners. For processes requiring special atmospheres, they can even operate with very rich (50% excess fuel) or lean (1500% excess air). They can be built to allow very high velocities (420,000 scfh/in.^{2} of refractory nozzle opening) for emphasizing convection heat transfer. (See Fig. 44.12.) Others use centrifugal and coanda effects to cause the flame to scrub an adjacent refractory wall contour, thus enhancing wall radiation. (See Fig. 44.13.) By engineering the mixing configuration, nozzle-mix burner designers are able to provide a wide range of mixing rates, from a fast, intense ball of flame ($L/D = 1$) to conventional feather-shaped flame ($L/D = 5$–10) to long flames ($L/D =$ 20–50). Changeable flame patterns are also possible.

Delayed-mix burners are a special form of nozzle mix, in which mixing is intentionally slow. (A raw gas torch is an unintentional form of delayed mixing.) Ignition of a fuel with a shortage of air results in polymerization or thermal cracking that forms soot particles only a few microns in diameter. These solids in the flame absorb heat and glow immediately, causing a delayed mix flame to be yellow or orange. The added luminosity enhances flame radiation heat transfer, which is one of the reasons for using delayed-mix flames. The other reason is that delayed mixing permits stretching the heat release over a great distance for uniform heating down the length of a radiant tube or a long kiln or furnace that can only be fired from one end.

Fuel-Directed Burners

Most industrial process burners have traditionally used energy from the air stream to maintain flame stability and flame shape. Now that most everyone has access to higher-pressure fuel supplies, it

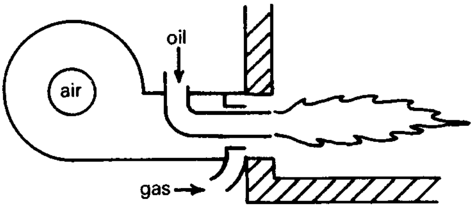

Fig. 44.8 Integral fan burner.

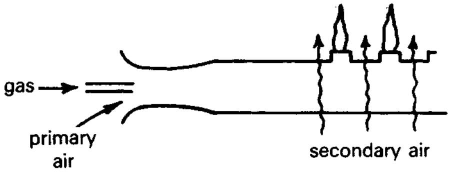

Fig. 44.9 Premix burners with inspirator mixer.

makes sense to use the energy in the fuel stream for controlling flame stability and shape, thereby permitting use of lower pressure air sources.

Figure 44.14 shows a fuel-directed burner for gas and preheated air. Multiple supply passages and outlet port positions permit changing the flame pattern during operation for optimum heat transfer during the course of a furnace cycle. Oil burners or dual-fuel combination burners can be constructed in a similar manner using two-fluid atomizers with compressed air or steam as the atomizing medium.

44.3.2 Burners for Liquid Fuels

Much of what has been said above for gas burners applies as well for oil burning. Liquids do not burn; therefore, they must be vaporized first. Kettle boiling or hot air can be used to produce a hot vapor stream that is directly substitutable for gas in premix burners. Unless there are many burners or they are very small, it is generally more practical (less maintenance) to convert to combination (dual-fuel) burners of the nozzle-mix type.

Vaporization by Atomization

Almost all industrial liquid fuel burners use atomization to aid vaporization by exposing the large surface area (relative to volume) of millions of droplets in the size range of 100–400 μm. Mass transfer then occurs at a rapid rate even if the droplets are not exposed to furnace radiation or hot air.

Pressure atomization (as with a garden hose) uses the pressure energy in the liquid steam to cause the kinetic energy to overcome viscous and surface tension forces. If input is turned down by reducing fuel pressure, however, atomizing quality suffers; therefore, this method of atomization is limited to on–off units or cases where more than 250 psi fuel pressure is available.

Two-fluid atomization is the method most commonly used in industrial burners. Viscous friction by a high-velocity second fluid surrounding the liquid fuel stream literally tears it into droplets. The second fluid may be low-pressure air (<2 psi, or <13.8 kPa), compressed air, gaseous fuel, or steam. Many patented atomizer designs exist—for a variety of spray angles, sizes, turndown ranges, droplet sizes. Emulsion mixing usually gives superior atomization (uniformly small drops with relatively small consumption of atomizing medium) but control is complicated by interaction of the pressures and flows of the two streams. External mixing is just the opposite. A compromise called tip-emulsion atomization is the current state of the art.

Rotary-cup atomization delivers the liquid fuel to the center of a fast spinning cup surrounded by an air stream. Rotational speed and air pressure determine the spray angle. This is still used in some large boilers, but the moving parts near the furnace heat have proved to be too much of a maintenance problem in higher-temperature process furnaces and on smaller installations where a strict preventive maintenance program could not be effected.

Sonic and ultrasonic atomization systems create very fine drops, but impart very little motion to them. For this reason they do not work well with conventional burner configurations, but require an all new design.

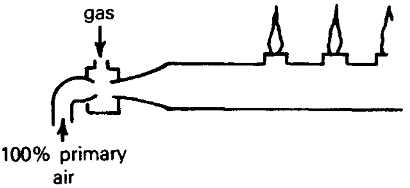

Fig. 44.10 Premix burners with aspirator mixer.

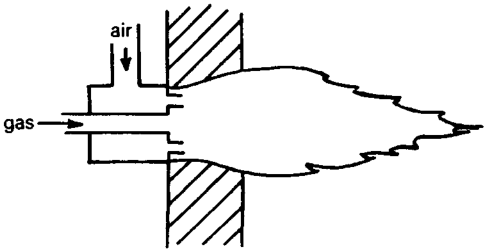

Fig. 44.11 Air-directed nozzle-mix burner.

Liquid Fuel Conditioning

A variety of additives can be used to reduce fuel degeneration in storage, minimize slagging, lessen surface tension, reduce pollution, and lower the dew point. Regular tank draining and cleaning and the use of filters are recommended.

Residual oils must be heated to reduce their viscosity for pumping, usually to 500 SSU (100 cSt). For effective atomization, burner manufacturers specify viscosities in the range of 100–150 SSU (22–32 cSt). In all but tropic climates, blended oils (Nos. 4 and 5) also require heating. In Arctic situations, distillate oils need heating. Figure 44.15 enables one to predict the oil temperature necessary for a specified viscosity. It is best, however, to install extra heating capacity because delivered oil quality may change.

Oil heaters can be steam or electric. If oil flow stops, the oil may vaporize or char. Either reduces heat transfer from the heater surfaces, which can lead to catastrophic failure in electric heaters. Oil must be circulated through heaters, and the system must be fitted with protective limit controls.

Hot oil lines must be insulated and traced with steam, induction, or resistance heating. The purpose of tracing is to balance heat loss to the environment. Rarely will a tracing system have enough capacity to heat up an oil line from cold. When systems are shut down, arrangements must be made to purge the heavy oil from the lines with steam, air, or (preferably) distillate oil. Oil standby systems should be operated regularly, whether needed or not. In cold climates, they should be started before the onset of cold weather and kept circulating all winter.

44.4 SAFETY CONSIDERATIONS

Operations involving combustion must be concerned about all the usual safety hazards of industrial machinery, plus explosions, fires, burns from hot surfaces, and asphyxiation. Less immediately severe, but long-range health problems related to combustion result from overexposure to noise and pollutants.

Preventing explosions should be *the* primary operating and design concern of *every* person in any way associated with combustion operations, because an explosion can be so devastating as to eliminate *all* other goals of anyone involved. The requirements for an explosion include the first five requirements for combustion (Table 44.3); therefore, striving to do a good job of combustion may set you up for an explosion. The statistical probability of having all seven explosion requirements at the same time and place is so small that people become careless, and therein lies the problem. Continuing training and retraining is the only answer.

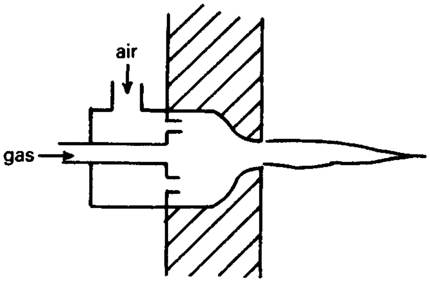

Fig. 44.12 High-velocity burner.

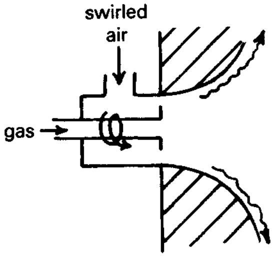

Fig. 44.13 Wall radiating burner (flat flame or coanda type).

The lower and upper limits of flammability are the same as the lower and upper explosive limits for any combustible gas or vapor. Table 46.3 lists these values for gases. Table 44.4 lists similar information for some common liquids. References 3, 4, and 5 list explosion-related data for many industrial solvents and off-gases.

Electronic safety control programs for most industrial combustion systems are generally designed (a) to prevent accumulation of unburned fuel when any source of ignition is present or (b) to immediately remove any source of ignition when something goes wrong, causing fuel accumulation. Of course, this is impossible in a furnace operating above 1400°F. If a burner in such a furnace should snuff out because it happened to go too rich, requirement number 3 is negated and there can be no explosion until someone (untrained) opens a port or shuts off the fuel. The only safe procedure is to gradually flood the chamber with steam or inert gas (gradually, so as not to change furnace pressure and thereby cause more air in-flow).

(a) The best way to prevent unburned fuel accumulation is to have a reliable automatic fuel–air ratio control system coordinated with automatic furnace pressure control and with input control so that input cannot range beyond the capabilities of either automatic system. The emergency back-up system consists of a trip valve that stops fuel flow in the event of flame failure or any of many other interlocks such as low air flow, or high or low fuel flow.

(b) Removal of ignition sources is implemented by automatic shutoff of other burner flames, pilot flames, spark igniters, and glow plugs. In systems where a single flame sensor monitors either main flame or pilot flame, the pilot flame must be programmed out when the main flame is proven. If this is not done, such a "constant" or "standing" pilot can "fool" the flame sensor and cause an explosion.

Most codes and insuring authorities insist on use of flame monitoring devices for combustion chambers that operate at temperatures below 1400°F. Some of these authorities point out that even high-temperature furnaces must go through this low-temperature range on their way to and from their

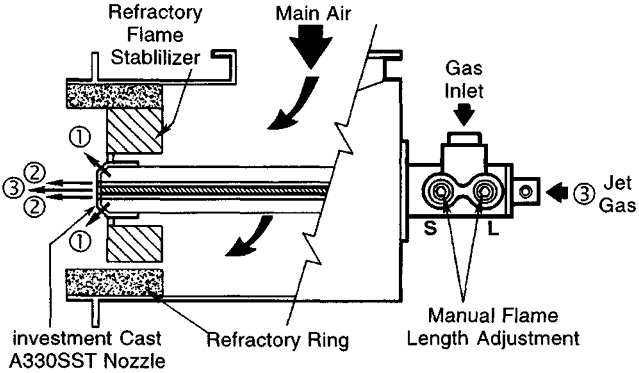

Fig. 44.14 Low NO_x fuel-directed gas burner for use with preheated air. ① Increasing tangential gas flow (adjustment screw S) shortens flame. ② Increasing forward gas flow (adjustment screw L) lengthens flame. ③ Jet gas—to maintain flame definition as input is reduced. (Courtesy of North American Mfg. Company.)

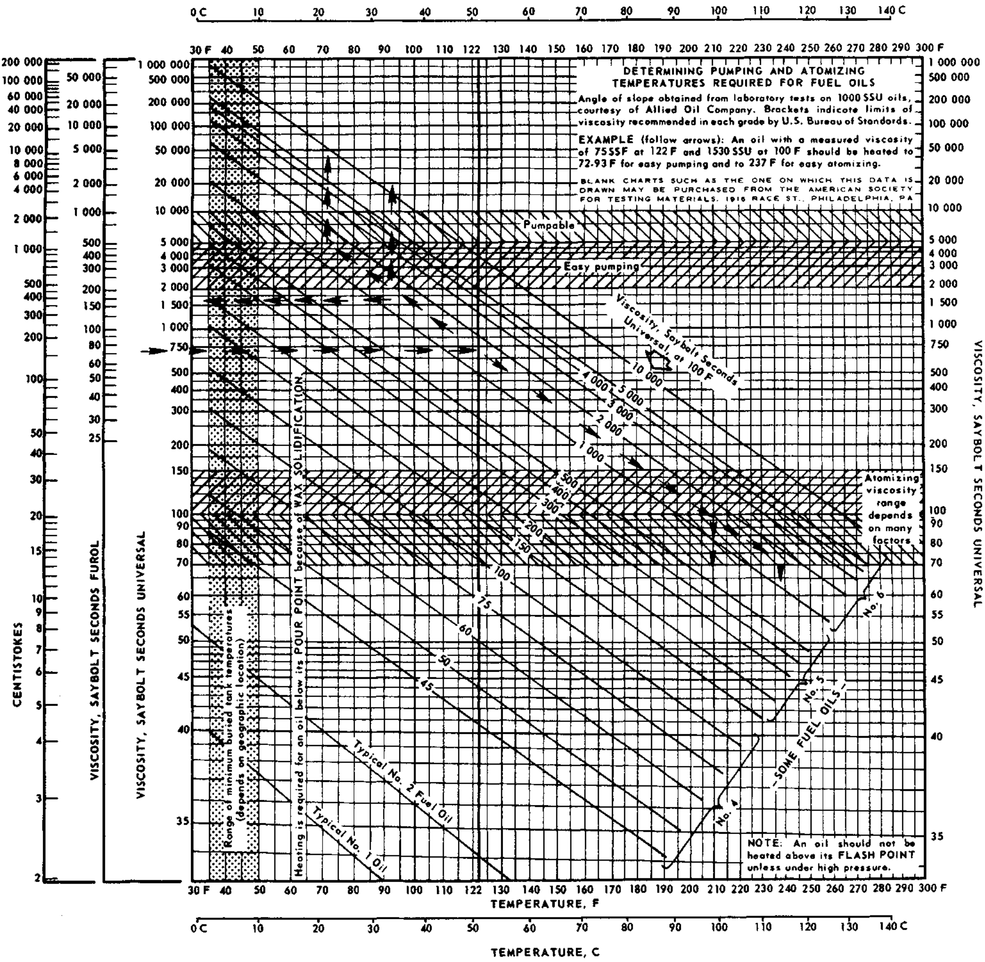

Fig. 44.15 Viscosity–temperature relations for typical fuel oils.

Table 44.3 Requirements for Combustion, Useful Combustion, and Explosion[a]

Requirements for Combustion	Requirements for Useful Combustion	Requirements for Explosion
1. Fuel	1. Fuel	1. Fuel
2. Oxygen (air)	2. Oxygen (air)	2. Oxygen (air)
3. Proper proportion (within flammability limits)	3. Proper proportion (within flammability limits)	3. Proper proportion (within explosive limits)
4. Mixing	4. Mixing	4. Mixing
5. Ignition	5. Ignition	5. Ignition
	6. Flame holder	6. Accumulation
		7. Confinement

[a] There have been incidents of disastrous explosions of unconfined fast-burning gases, but most of the damage from industrial explosions comes from the fragments of the containing furnace that are propelled like shrapnel. Lightup explosions are often only "puffs" if large doors are kept open during startup.

Table 44.4 Flammability Data for Liquid Fuels

Liquid Fuel	Flash Point, °F (°C) (Closed Cup Method)		Flammability Limits (%) Volume in Air		Autoignition Temperature, °F (°C)		Vapor density, G(air = 1)	Boiling Temperature, °F (°C)	
			Lower	Upper					
Butane, -*n*	−76	(−60)	1.9	8.5	761	(405)	2.06	31	(−1)
Butane, -iso	−117	(−83)	1.8	8.4	864	(462)	2.06	11	(−12)
Ethyl alcohol (ethanol)	55	(13)	3.5	19	737	(392)	1.59	173	(78)
Ethyl alcohol, 30% in water	85	(29)	3.6	10	—	—	—	203	(95)
Fuel oil, #1	114–185	(46–85)	0.6	5.6	445–560	(229–293)	—	340–555	(171–291)
Fuel oil (diesel), #1-D	>100	(>38)	1.3	6.0	350–625	(177–329)	—	<590	<310
Fuel oil, #2	126–230	(52–110)	—	—	500–705	(260–374)	—	340–640	(171–338)
Fuel oil (diesel), #2-D	>100	>38	1.3	6.0	490–545	(254–285)	—	380–650	(193–343)
Fuel oil, #4	154–240	(68–116)	1	5	505	(263)	—	425–760	(218–404)
Fuel oil, #5	130–310	(54–154)	1	5	—	—	—	—	—
Fuel oil, #6	150–430	(66–221)	1	5	765	(407)	—	—	—
Gasoline, automotive	−50±	(−46±)	1.3–1.4	6.0–7.6	700	(371)	3–4	91–403	(33–206)
Gasoline, aviation	−50±	(−46±)	1	6.0–7.6	800–880	(427–471)	3–4	107–319	(42–159)
Jet fuel, JP-4	−2	(−19)	0.8	6.2	468	(242)	—	140–490	(60–254)
Jet fuel, JP-5	105	(41)	0.6	4.6	400	(204)	—	370–530	(188–277)
Jet fuel, JP-6	127	(53)	—	—	500	(260)	—	250–500	(121–260)
Kerosene	110–130	(43–54)	0.6	5.6	440–560	(227–293)	4.5	350–550	(177–288)
Methyl alcohol (methanol)	54	(12)	5.5	36.5	878	(470)	1.11	147	64
Methyl alcohol, 30% in water	75	(24)	—	—	—	—	—	167	75
Naphtha, dryclean	100–110	(38–43)	0.8	5.0	440–500	(227–260)	—	300–400	(149–204)
Naphtha, 76%, vm&p	20–45	(−7–+7)	0.9	6.0	450–500	(232–260)	3.75	200–300	(93–149)
Nonane, -*n*	88	(31)	0.74	2.9	403	(206)	4.41	303	(151)
Octane, -iso	10	(−12)	1.0	6.0	784	(418)	3.93	190–250	(88–121)
Propane	−156	(−104)	2.2	9.6	871	(466)	1.56	−44	(−42)
Propylene	−162	(−108)	2.0	11.1	927–952	(497–511)	1.49	−54	(−48)

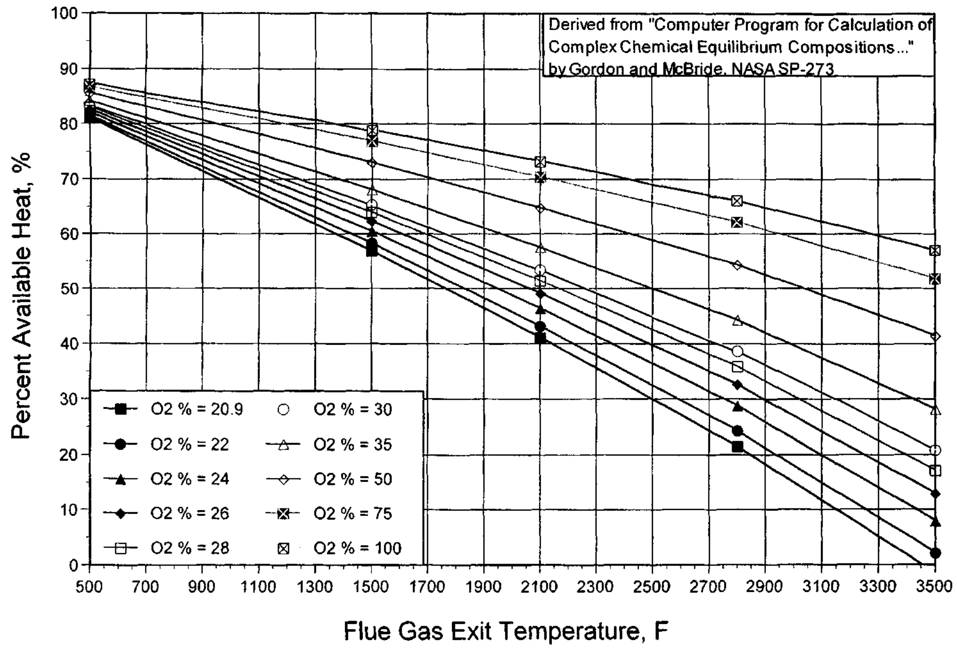

Fig. 44.16 Percents available heat for Phi = .95 or 5% excess air with average natural gas, HHV = 1025 Btu/cu ft, with various degrees of oxygen enrichment and for oxy-fuel firing (top curve).

normal operating temperature. Another situation where safety regulations and economic reality have not yet come to agreement involves combustion chambers with dozens or even hundreds of burners, such as refinery heaters, ceramic kilns, and heat-transfer furnaces.

Avoiding fuel-fed fires first requires preventing explosions, which often start such fires. (See previous discussion.) Every building containing a fuel-fired boiler, oven, kiln, furnace, heater, or incinerator should have a spring-operated manual reset fuel shutoff valve outside the building with panic buttons at the guardhouse or at exits to allow shutting off fuel as one leaves the burning building. Gas-fuel lines should be overhead where crane and truck operators cannot rupture them, or underground. If underground, keep and use records of their locations to avoid digging accidents. Overhead fuel lines must have well-marked manual shutoff valves where they can be reached without a ladder. Liquid-fuel lines should be underground; otherwise, a rupture will pour or spray fuel on a fire.

The greatest contributor to fuel-fed fires is the fuel shutoff valve that will not work. All such valves, manual or automatic, must be tested on a regular maintenance schedule. Such testing may cause nuisance shutdowns of related equipment; therefore, a practical procedure is to have the maintenance crew do the day's end (or week's end) shutdown about once each month. The same test can check for leaking. If it is a fully automatic or manual-reset automatic valve, shutdown should be accomplished by simulating flame failure and, in succession, each of the interlocks.

Because so much depends on automatic fuel shutoff valves, it makes sense (a) to have a backup valve (blocking valve), and (b) to replace it before it hangs up—at least every 5 years, more often in adverse environments.

Maintenance and management people must be ever alert for open side panels and covers on safety switches and fuel shutoff valves. Remove wedges, wires, or blocks that are holding circuits closed or valves open. Remove jumper wires unless the manufacturer's wiring diagram specifies that they be left in. Eliminate valve by-passes unless they contain a similar valve. Then, get to the root of the problem by finding the cause of the nuisance that caused someone to try to bypass the safety system.

Storage of LP gas, oils, or solid fuels requires careful attention to applicable codes. If the point of use, an open line, or a large leak is below the oil storage elevation, large quantities may siphon out and flow into an area where there is a water heater or other source of ignition. Steam heaters in heavy oil tanks need regular inspections, or leaks can emulsify the oil, causing an overflow. It is advisable to make provision for withdrawing the heater for repair without having to drain the whole tank.

LP gas is heavier than air. Workers have been suffocated by this invisible gas when it leaked into access pits below equipment.

Codes and regulations are proliferating, many by local authorities or insuring groups. Most refer, as a base, to publications of the NFPA, the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269. Their publications usually represent the consensus of technically competent volunteer committees from industries involved with the topic.

44.5 OXY-FUEL FIRING

Commercially "pure" oxygen (90–99% oxygen) is sometimes substituted for air (20.9% oxygen), (a) to achieve higher flame temperature, (b) to get higher % available heat (best possible efficiency), or (c) to try to eliminate nitrogen from the furnace atmosphere, and thereby reduce the probability of NO_x pollution.

Figure 44.16 shows percents available heat and adiabatic flame temperatures (x-intercepts) for various amounts of oxygen enrichment of an existing air supply, and for "oxy-fuel firing". The latter is with 100% oxygen, and is the only way to use oxygen to reduce NO_x; oxygen enrichment usually causes more NO_x.

Oxy-fuel burners have been water-cooled in the past, but their propensity to spring leaks and do terrible damage has led to use of better materials to avoid water cooling. Oxygen burner nozzles and tiles are subject to much higher temperatures and more oxidizing atmospheres than are air burner nozzles and tiles. Control valves, regulators, and piping for oxygen require special cleaning and material selection.

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