

## SECTION 8

# Fired Equipment

Fired equipment transfers heat produced by combustion of the fuel to the process stream. In gas processing equipment, the fuel is usually natural gas; however, ethane, propane, or light oils are sometimes used. The process stream varies widely, e.g., natural gas, heavier hydrocarbons, water, glycol, amine solutions, heat transfer oils, and molten salts.

Fired equipment can be classified as:

1. Direct fired heaters where the combustion gases occupy most of the heater volume and heat the process stream contained in pipes arranged in front of refractory walls — the radiant section — and in a bundle in the upper portion — the convection section. Convective heaters are a special application in which there is only a convection section.

**FIG. 8-1**  
**Nomenclature**

|                                                                                                           |                                                                                                  |
|-----------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|
| a = tube arrangement constant, Equation 8-21                                                              | I = average tube radiant heat flux intensity (circumferential), Btu/(hr · sq ft)                 |
| A = area, sq ft                                                                                           | k = thermal conductivity, Btu/[(hr · sq ft · °F)/ft]                                             |
| AO = dry combustion air mols per dry fuel mols, for stoichiometric combustion, mols/mols                  | L = length of heat transfer surface, ft; or                                                      |
| B = parameter defined by Equation 8-21                                                                    | = mean beam length, ft; or                                                                       |
| c = number of carbon atoms in fuel molecule                                                               | = characteristic dimension, ft                                                                   |
| C = Nusselt equation constant, Equation 8-4 and Equation 8-8                                              | LHV = lower or net heating value, Btu/SCF                                                        |
| C <sub>d</sub> = burner spud discharge coefficient                                                        | LNB = low NO <sub>x</sub> burner                                                                 |
| C <sub>p</sub> = specific heat, Btu/(lb · °F)                                                             | m = Nusselt equation constant, Equation 8-4 and Equation 8-8                                     |
| CO = carbon monoxide mols in mols of dry flue gases, mols/mols                                            | M = mass flow rate, lb/hr                                                                        |
| CO <sub>2</sub> = carbon dioxide mols in mols of dry flue gases, mols/mols                                | MPH = velocity, miles/hr                                                                         |
| CO <sub>2o</sub> = carbon dioxide mols in mols of dry flue gases for stoichiometric combustion, mols/mols | n = number of fins per foot, number of tube rows                                                 |
| d = diameter of pipe or cylinder or fin or sphere, in.                                                    | ni = number of nitrogen atoms in fuel molecule                                                   |
| D = diameter of pipe or cylinder or sphere, ft                                                            | Nu = Nusselt number, dimensionless                                                               |
| EA = volume percentage of excess combustion air, %                                                        | NHI = net heat input, Btu/hr                                                                     |
| f <sub>f</sub> = Fanning friction factor                                                                  | NPS = nominal pipe size, in.                                                                     |
| F = view factor, dimensionless                                                                            | NTE = net thermal efficiency, Equation 8-17b                                                     |
| FGR = flue gas recirculation                                                                              | o = number of oxygen atoms in fuel molecule                                                      |
| Fl <sub>o</sub> = mols of dry flue gases per mols of dry fuel for stoichiometric combustion, mols/mols    | O <sub>2</sub> = oxygen mols in mols of dry flue gases, mols/mols                                |
| g = acceleration due to gravity = 32.17 ft/sec <sup>2</sup>                                               | O <sub>2o</sub> = oxygen mols in mols of dry flue gases for stoichiometric combustion, mols/mols |
| g <sub>c</sub> = 32.17 lb mass · ft/(lb force · sec <sup>2</sup> )                                        | P = partial pressure of CO <sub>2</sub> + H <sub>2</sub> O, atm                                  |
| G = Ratio of air to fuel, lb/lb; or                                                                       | P <sub>B</sub> = barometric pressure, in. Hg @ 32°F                                              |
| = mass velocity, lb/(sec · sq ft)                                                                         | ΔP = pressure difference, psi                                                                    |
| GHI = gross heat input, Btu/hr                                                                            | P <sub>g</sub> = burner fuel gas pressure, psia                                                  |
| GTE = gross thermal efficiency, Equation 8-17a                                                            | Pr = Prandtl number, dimensionless                                                               |
| Gr = Grashof number, dimensionless                                                                        | q <sub>gs</sub> = gas flow rate at standard conditions, SCF/day                                  |
| h = heat transfer coefficient, Btu/(hr · sq ft · °F)                                                      | q <sub>l</sub> = liquid flow rate, gals/min                                                      |
| H = heat content or enthalpy, Btu/lb; or                                                                  | Q = heat transfer or heat input or heat content (rates), Btu/hr                                  |
| = height of stack, ft; height of fin, in.                                                                 | r = ratio of flue gases to heat release, lb/MMBtu                                                |
| HAP = hazardous air pollutant                                                                             | rf = fouling heat flow resistance, hr · sq ft · °F/Btu                                           |
| Hav = available draft, inches water column (gauge)                                                        | R = fraction of total heat liberation absorbed in radiant section (Fig. 8-23)                    |
| HHV = higher or gross heating value, Btu/SCF                                                              | Re = Reynolds number, dimensionless                                                              |
| hy = number of hydrogen atoms in fuel molecule                                                            | s = number of sulfur atoms in fuel molecule                                                      |
|                                                                                                           | S = tube spacing, in.                                                                            |

**FIG. 8-1 (Cont'd)**  
**Nomenclature**

SCF = standard cubic feet at 14.696 psia and 60°F  
 SG = specific gravity  
 t = fin thickness, in.  
 T = temperature, °R  
 ΔT = temperature difference, °F  
 U = overall heat transfer coefficient, Btu/(hr · sq ft · °F)  
 UHT = useful heat transferred or heat duty, Btu/hr  
 V = velocity, ft/sec  
 w = weight of air, lb  
 wt = wall thickness, in.  
 Δx = distance in direction of heat transfer, ft or in.  
 Y = expansion factor, dimensionless

**Greek**

β = volumetric coefficient of thermal expansion, 1/°F  
 ε<sub>1</sub>, ε<sub>2</sub> = emissivities of combustion gases and wall, respectively  
 μ = viscosity of fluid, cp  
 ρ = density of fluid, lb/cu ft  
 σ = Stefan-Boltzmann constant, 0.171 (10<sup>-8</sup>) Btu/(hr · sq ft · °R<sup>4</sup>)  
 π = 3.1416

**Subscripts**

a = atmospheric air at operating conditions  
 as = air at standard conditions  
 B = barometric  
 b = bulk  
 c = convective  
 cs = cross section (projection)  
 f = fin; fouling; friction; Fanning  
 g = gas  
 gs = gas at standard conditions  
 i = inside, internal  
 LM = log mean base e  
 m = middle surface  
 o = outside, external, overall  
 p = pipe  
 r = radiant  
 s = stack  
 w = wall  
 1 = burner operating conditions 1  
 2 = burner operating conditions 2

2. Firetube heaters where the combustion gases are contained in a firetube that is surrounded by a liquid that fills the heater shell. This liquid may be either the process stream or a heat transfer medium that surrounds the coil bundle containing the process stream.

Fig. 8-2 lists the common applications and general characteristics of these heaters.

**FIG. 8-2**

**Heater Applications and Characteristics**

| Direct Fired                                                                                                                         | Firetube                                                                                                                                                                                       |
|--------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Applications                                                                                                                         |                                                                                                                                                                                                |
| Hot oil heater<br>Regeneration gas heaters<br>Amine and stabilizer reboilers                                                         | Indirect fired water bath heaters (line heaters)<br>Propane and heavier hydrocarbon vaporizers<br>Hot oil and salt bath heaters<br>Glycol and amine reboilers<br>Low pressure steam generators |
| Characteristics                                                                                                                      |                                                                                                                                                                                                |
| More ancillary equipment and controls<br>Higher thermal efficiency<br>Requires less plot space<br>Forced or natural draft combustion | Heat duty usually less than 10 MMBtu/hr<br>Easily skid mounted<br>Forced or natural draft combustion<br>Less likely to have hot spots or tube rupture                                          |

## HEAT TRANSFER

### Conduction

Fourier's law of conduction gives the rate of heat transfer through substances resulting from vibrations and interactions between adjacent molecules as opposed to overall motion or mixing of the molecules. Conduction always applies to solids and rarely to fluids.

Fundamental equations for steady heat conduction through some common solid shapes, ignoring border conditions, are:

For unidimensional perpendicular heat flow through flat walls, as in heat flow through a square or very large cylindrical tank wall:

$$Q = 12 \cdot k \cdot A \cdot \frac{\Delta T}{wt} \quad \text{Eq 8-1}$$

For heat transfer in cylindrical geometry where the heat transfer is normal to the axis, as in heat flow through a cylindrical vessel or pipe wall:

$$Q = \frac{2 \cdot \pi \cdot L \cdot k \cdot \Delta T}{\ln (D_o/D_i)} = \frac{2 \cdot \pi \cdot L \cdot k \cdot \Delta T}{\ln (d_o/d_i)} \quad \text{Eq 8-2a}$$

For radial heat flow through a spherical vessel:

$$Q = \frac{2 \cdot \pi \cdot k \cdot \Delta T}{(1/D_i) - (1/D_o)} = \frac{\pi \cdot k \cdot \Delta T}{(6/d_i) - (6/d_o)} \quad \text{Eq 8-2b}$$

Fig. 8-3 gives the thermal conductivities and densities of commercial refractories and insulation. Similar data for metals are given in Fig. 8-8 and Fig. 8-9.

**FIG. 8-3**  
**Properties of Commercial Refractories and Insulations**

| Products                     | Max Service Temp, °F (Note 1) | Thermal Conductivity, Btu/[(hr • ft <sup>2</sup> • °F)/in] at Mean Temperature, °F (Note 16) |      |      |      |      | Density, lb/ft <sup>3</sup> | Cold Crush Strength, lb/in <sup>2</sup> | Notes   |
|------------------------------|-------------------------------|----------------------------------------------------------------------------------------------|------|------|------|------|-----------------------------|-----------------------------------------|---------|
|                              |                               | 500                                                                                          | 1000 | 1500 | 2000 | 2500 |                             |                                         |         |
| <b>FIREBRICK</b>             |                               |                                                                                              |      |      |      |      |                             |                                         |         |
| H-W Karundal XD              | 3300                          | 24.4                                                                                         | 20.4 | 19.6 | 19.6 | 19.7 | 187                         | 15600                                   | 2       |
| H-W UFALA                    | 3000                          | 13.0                                                                                         | 12.8 | 13.1 | 13.6 | 14.4 | 157                         | 7000                                    |         |
| APGreen KX-99                | 2500                          | 9.7                                                                                          | 9.9  | 10.2 | 10.7 | 11.1 | 143                         | 10700                                   |         |
| APGreen Empire S             | 2400                          | 8.3                                                                                          | 8.8  | 9.2  | 9.5  | 9.9  | 132                         | 2100                                    |         |
| <b>INSULATING BRICK</b>      |                               |                                                                                              |      |      |      |      |                             |                                         |         |
| APGreen Greenlite 30         | 3000                          | 2.6                                                                                          | 3.1  | 3.6  | 4.0  | 4.5  | 61                          | 1175                                    |         |
| Thermal Ceramics K-25        | 2500                          | 1.1                                                                                          | 1.3  | 1.5  | 1.7  |      | 38                          | 220                                     |         |
| Thermal Ceramics K-23        | 2300                          | 1.0                                                                                          | 1.2  | 1.5  | 1.7  |      | 31                          | 145                                     |         |
| Thermal Ceramics K-20        | 2000                          | 0.9                                                                                          | 1.1  | 1.4  |      |      | 29                          | 125                                     |         |
| <b>HEAVY CASTABLE</b>        |                               |                                                                                              |      |      |      |      |                             |                                         |         |
| APGreen Greencast 94         | 3400                          | 14.5                                                                                         | 12.6 | 11.3 | 10.7 | 10.8 | 163                         | 5800                                    | 2,3,4,5 |
| APGreen Mizzou               | 3000                          | 7.8                                                                                          | 7.7  | 7.5  | 7.4  | 7.4  | 139                         | 3000                                    | 3,11    |
| <b>LIGHT CASTABLE</b>        |                               |                                                                                              |      |      |      |      |                             |                                         |         |
| APGreen Kast-O-Lite 25       | 2600                          | 3.6                                                                                          | 3.5  | 3.7  | 4.0  |      | 86                          | 1300                                    | 8       |
| APGreen 45-L                 | 2500                          | 2.7                                                                                          | 2.6  | 2.5  |      |      | 71                          | 2500                                    | 3,6,7,8 |
| APGreen Castable 22          | 2200                          | 1.7                                                                                          | 1.9  | 2.2  | 2.5  |      | 53                          | 275                                     | 3,8     |
| APGreen Cast Block Mix       | 1600                          | 0.6                                                                                          | 1.0  | 1.5  |      |      | 22                          | 20                                      | 8       |
| <b>GUN &amp; RAM MIXES</b>   |                               |                                                                                              |      |      |      |      |                             |                                         |         |
| Premier 85 RAM HS            | 3000                          | 21.7                                                                                         | 14.1 | 12.6 | 11.9 | 12.1 | 175                         | 5000                                    | 5,9     |
| H-W Tuff Shot LI             | 2600                          | 6.2                                                                                          | 6.5  | 6.7  | 6.8  | 6.9  | 119                         | 3450                                    | 6,11    |
| APGreen Kast-O-Lite 26-LI GR | 2600                          | 3.6                                                                                          | 3.7  | 3.9  | 4.3  |      | 92                          | 2000                                    |         |
| <b>CERAMIC FIBER</b>         |                               |                                                                                              |      |      |      |      |                             |                                         |         |
| Thermal Ceramics Saffl       | 2800                          | 0.38                                                                                         | 0.7  | 1.0  | 1.5  | 2.3  | 3                           |                                         | 4       |
| Fiberfrax Durablanket 2600   | 2600                          | 0.51                                                                                         | 1.15 | 2.18 | 3.56 |      | 6                           |                                         |         |
| Fiberfrax Durablanket 2600   | 2600                          | 0.51                                                                                         | 0.98 | 1.81 | 2.96 |      | 8                           |                                         |         |
| Fiberfrax 550 Paper          | 2300                          | 0.42                                                                                         | 0.75 | 1.33 | 2.12 |      | 12                          |                                         |         |
| Thermal Cer Cerablanket      | 2150                          | 0.5                                                                                          | 1.0  | 1.7  | 2.6  |      | 6                           |                                         |         |
| Thermal Cer Cerablanket      | 2150                          | 0.37                                                                                         | 0.8  | 1.5  | 2.1  |      | 8                           |                                         |         |
| <b>BLOCK &amp; BOARD</b>     |                               |                                                                                              |      |      |      |      |                             |                                         |         |
| Fiberfrax Duraboard LD       | 2300                          | 0.56                                                                                         | 0.85 | 1.24 | 0.73 |      | 16                          | 50                                      |         |
| Fiberfrax Duraboard HD       | 2300                          | 0.56                                                                                         | 0.85 | 1.47 | 1.61 |      | 26                          | 70                                      |         |
| Thermal Ceramics TR-20       | 2000                          | 0.64                                                                                         | 0.77 | 0.92 |      |      | 25                          | 201                                     | 12      |
| USG K-FAC 19                 | 1900                          | 0.51                                                                                         | 0.89 |      |      |      | 18.5                        | 33                                      | 10,13   |
| Schuller Thermo 12           | 1200                          | 0.45                                                                                         | 0.64 |      |      |      | 15                          | 160                                     | 10,14   |
| PARTEK Paroc 1212            | 1200                          | 0.42                                                                                         | 0.98 |      |      |      | 12                          |                                         | 10,13   |
| Schuller 1000 SpinGlas       | 850                           | 0.50                                                                                         |      |      |      |      | 3                           |                                         | 10,15   |

**NOTES**

- Maximum Service Temperature listed has no safety factor included.
- 90-94% Alumina product for extreme temperature or high velocity service
- Cast properties listed, gunning product available but properties will be different.
- Low silica product.
- For burner blocks and severe service.
- Can be used as one shot (single layer) lining.
- High performance medium weight lining.
- May be used as back-up insulation in 2 layer lining.
- 85% Alumina ramming plastic for burner blocks, etc.
- For external insulation only.
- May be used as hot face lining in dual layer system.
- Diatomaceous earth base.
- Mineral wool base.
- Calcium silicate base.
- Fiber glass base.
- Convert to Btu/[(hr • ft<sup>2</sup> • °F)/ft] before using in equations in this section.

**Example 8-1** — Estimate the loss per linear foot through a one inch layer of block insulation covering an 8 in. Sch 40 steam header. Assume:

$$T_i = 250^\circ\text{F}$$

$$T_o = 50^\circ\text{F}$$

$$k = 0.0417 \text{ Btu}/[(\text{hr} \cdot \text{sq ft} \cdot ^\circ\text{F})/\text{ft}]$$

(Both ft and in. are usually used in the thermal conductivity units for insulating materials; the following equations use ft.)

### Solution Steps

From Equation 8-2a

$$\begin{aligned} Q &= \frac{2 \cdot \pi \cdot k \cdot \Delta T}{\ln(d_o/d_i)} \\ &= \frac{2 \cdot \pi \cdot (0.0417) (250-50)}{\ln(10.625/8.625)} \\ &= 251.2 \text{ Btu / hr per linear ft} \end{aligned}$$

### Convection

Heat transfer between a solid and an adjacent fluid occurs by movement of the fluid molecules. Hot molecules leave the surface of the solid and are replaced by cold ones. Most of the resistance to this form of heat transfer occurs in a thin film or layer next to the solid surface. This layer exists even if the bulk fluid flow is violently turbulent.

Newton's law of cooling applies to convective heat transfer

$$Q = h \cdot A \cdot \Delta T \quad \text{Eq 8-3}$$

**Natural or free convection** — occurs when the only force promoting the fluid flow results from temperature differences in the fluid. Under these conditions the heat transfer coefficient is obtained from the Nusselt equation.

$$\text{Nu} = C (\text{Gr} \cdot \text{Pr})^m \quad \text{Eq 8-4}$$

Where

$$\text{Nu} = \frac{h \cdot D_o}{k} = \frac{h \cdot d_o}{12 \cdot k} \quad \text{Eq 8-5a}$$

$$\text{or } \text{Nu} = \frac{h \cdot L}{k} \quad \text{Eq 8-5b}$$

$$\begin{aligned} \text{Gr} &= \frac{2.214 \cdot 10^6 \cdot D_o^3 \cdot \rho^2 \cdot g \cdot \beta \cdot \Delta T}{\mu^2} \\ &= \frac{1281 \cdot d_o^3 \cdot \rho^2 \cdot g \cdot \beta \cdot \Delta T}{\mu^2} \end{aligned} \quad \text{Eq 8-6a}$$

$$\text{or } \text{Gr} = \frac{2.214 \cdot 10^6 \cdot L^3 \cdot \rho^2 \cdot g \cdot \beta \cdot \Delta T}{\mu^2} \quad \text{Eq 8-6b}$$

$$\text{Pr} = \frac{2.419 \cdot C_p \cdot \mu}{k} \quad \text{Eq 8-7}$$

The constants C and m depend on the shape and size of the solid surface, the orientation of the surface to the fluid, whether the solid is hotter than the fluid or vice versa, and the magnitude of (Gr · Pr). A brief summary of C and m for some usual situations is given in Fig. 8-4.

**FIG. 8-4**  
**Heat Transfer Constants<sup>2</sup> for Equation 8-4**  
**(Natural or Free Convection)**

| Configuration                                               | D or Y (Y = Gr · Pr)       | C    | m    |
|-------------------------------------------------------------|----------------------------|------|------|
| Vertical Plates or Cylinders                                | $Y < 10^4$                 | 1.36 | 0.20 |
|                                                             | $10^4 < Y < 10^9$          | 0.55 | 0.25 |
|                                                             | $10^9 < Y$                 | 0.13 | 0.33 |
| Horizontal Plates:<br>Facing Up<br>Facing Up<br>Facing Down | $10^5 < Y < 2(10^7)$       | 0.54 | 0.25 |
|                                                             | $2(10^7) < Y < 3(10^{10})$ | 0.14 | 0.33 |
|                                                             | $3(10^5) < Y < 3(10^{10})$ | 0.27 | 0.25 |
| Long Horizontal Cylinders<br>L > D                          | $D < 0.1$                  | 0.53 | 0.25 |
|                                                             | $0.1 < D < 0.5$            | 0.47 | 0.25 |
|                                                             | $0.5 < D$                  | 0.11 | 0.33 |
| Short Horizontal Cylinders<br>L = D < 8 in.                 | $Y < 10^{-5}$              | 0.49 | 0.00 |
|                                                             | $10^{-5} < Y < 10^{-3}$    | 0.71 | 0.04 |
|                                                             | $10^{-3} < Y < 1$          | 1.09 | 0.10 |
|                                                             | $1 < Y < 10^4$             | 1.09 | 0.20 |
|                                                             | $10^4 < Y < 10^9$          | 0.53 | 0.25 |
|                                                             | $10^9 < Y$                 | 0.13 | 0.33 |

Nu, Gr, and Pr are dimensionless when the units indicated in Fig. 8-1 are used in equations 8-4 through 8-7. The physical properties are those of the fluid at the film temperature, which is often assumed to be the average of the solid surface and bulk fluid temperatures. Fluid properties may have to be evaluated at an assumed film temperature, and this assumption then confirmed from the results — see Example 8-4.

The coefficient of thermal expansion  $\beta$  for low pressure gas (i.e. ideal gas) equals  $1/(T, ^\circ\text{R})$ . It is left in this form for use in Gr and is not converted to  $1/^\circ\text{F}$  for dimensional consistency.

**Example 8-2** — What is the heat transfer coefficient for natural convection around a 3 in. Sch 40 pipe surrounded by water at  $190^\circ\text{F}$ ? Assume  $T_o$  for the pipe is  $114^\circ\text{F}$ .

### Solution Steps

$$T_{\text{film}} = (190 + 114)/2 = 152^\circ\text{F} (612^\circ\text{R})$$

From Equation 8-4, 8-5a, 8-6a and 8-7 and Fig. 8-4:

$$\text{Nu} = 0.47 (\text{Gr} \cdot \text{Pr})^{0.25}$$

$$\frac{h_o \cdot d_o}{12 \cdot k} = 0.47 \left[ \frac{1281 \cdot d_o^3 \cdot \rho^2 \cdot g \cdot \beta \cdot \Delta T \cdot C_p \cdot 2.419}{\mu \cdot k} \right]^{0.25}$$

$$d_o = 3.5 \text{ in.}$$

$$\rho = 61.8 \text{ lb / cu ft}$$

$$g = 32.17 \text{ ft / sec}^2$$

$$\beta = 0.00035^\circ\text{F}^{-1}$$

$$\Delta T = 190 - 114 = 76^\circ\text{F}$$

$$C_p = 1.00 \text{ Btu / (lb} \cdot ^\circ\text{F)}$$

$$\mu = 0.63 \text{ cp}$$

$$k = 0.365 \text{ Btu / [(hr} \cdot \text{sq ft} \cdot ^\circ\text{F}) / \text{ft}]$$

The properties of water ( $\rho$ ,  $\beta$ ,  $\mu$ ,  $k$ ) are based on the film temperature.

Substituting:

$$h_o = \frac{(12)(0.47)(0.365)}{3.5} \left[ \frac{1281(3.5)^3 (61.8)^2 (32.17) (0.00035) (76) (1.0) (2.419)}{(0.63)(0.365)} \right]^{0.25}$$

$$= 0.588 [1.889 (10^9)]^{0.25}$$

$$= 122.6 \text{ Btu} / (\text{hr} \cdot \text{sq ft} \cdot ^\circ\text{F})$$

**Forced convection** — occurs when the fluid flow adjacent to a solid is promoted by external force, e.g., pumping, agitation, etc. The result is a substantial increase in the heat transfer rate. The Dittus-Boelter correlation is:

$$\text{Nu} = C \cdot \text{Re}^m \cdot \text{Pr}^{0.33} \quad \text{Eq 8-8a}$$

Utilization of a viscosity correction term gives the Sieder-Tate correlation:

$$\text{Nu} = C \cdot \text{Re}^m \cdot \text{Pr}^{0.33} (\mu_b / \mu_w)^{0.14} \quad \text{Eq 8-8b}$$

Where

$$\text{Re} = \frac{1488 \cdot D \cdot V \cdot \rho}{\mu} = \frac{124 \cdot d \cdot V \cdot \rho}{\mu} \quad \text{Eq 8-9a}$$

$$= \frac{0.5263 \cdot M}{D \cdot \mu} = \frac{6.316 \cdot M}{d \cdot \mu}$$

$$= \frac{4.221 \cdot q_l \cdot \rho}{D \cdot \mu} = \frac{50.66 \cdot q_l \cdot \rho}{d \cdot \mu}$$

$$= \frac{q_{gs} \cdot \text{SG}}{598 \cdot D \cdot \mu} = \frac{0.02007 \cdot q_{gs} \cdot \text{SG}}{d \cdot \mu}$$

or

$$\text{Re} = \frac{1488 \cdot L \cdot V \cdot \rho}{\mu} \quad \text{Eq 8-9b}$$

Equation 8-8b need be used only for high viscosity fluids such as glycol.

As before, Re is dimensionless when the units indicated in Fig. 8-1 are used in equations 8-9a and 8-9b. The constants C and m depend on the configuration and the type of fluid flow — laminar, intermediate, or turbulent — which is characterized by the magnitude of the Reynolds number. Fig. 8-5 lists values for the more common situations.

**Example 8-3** — Find the heat transfer coefficient for 10 MMscfd of 0.6 gravity natural gas flowing at 2000 psia in a 3 in. Sch 80 pipe when the pipe wall and gas temperatures are 104 and 72°F, respectively.

### Solution Steps

$$T_{\text{film}} = (104 + 72)/2 = 88^\circ\text{F}$$

From Equation 8-7, 8-8a and 8-9a and Fig. 8-5:

$$\text{Nu} = 0.023 (\text{Re})^{0.8} (\text{Pr})^{0.33}$$

$$\frac{h_i \cdot d_i}{12 \cdot k} = 0.023 \left( \frac{0.02 \cdot q_{gs} \cdot \text{SG}}{d_i \cdot \mu} \right)^{0.8} \left( \frac{2.419 \cdot C_p \cdot \mu}{k} \right)^{0.33}$$

where:  $d_i = 2.90 \text{ in.}$

$$\text{SG} = 0.6$$

$$\mu = 0.019 \text{ cp}$$

$$k = 0.03 \text{ Btu} / (\text{hr} \cdot \text{sq ft} \cdot ^\circ\text{F}) / \text{ft}$$

$$C_p = 0.73 \text{ Btu} / (\text{lb} \cdot ^\circ\text{F})$$

$$q_{gs} = 10 (10^6) \text{ scfd}$$

$$\text{Re} = \frac{0.02 \cdot q_{gs} \cdot \text{SG}}{d \cdot \mu}$$

$$= \frac{0.02 (10) (10^6) 0.6}{2.9 (0.019)} = 2.18 (10^6)$$

$$\text{Pr} = \frac{2.419 \cdot C_p \cdot \mu}{k} = \frac{2.419 \cdot 0.73 \cdot 0.019}{0.03}$$

$$= 1.118$$

$$h_i = \frac{(0.023) (12) (0.03)}{2.9} [2.18 (10^6)]^{0.8} (1.118)^{0.33}$$

$$= 349.9 \text{ Btu} / (\text{hr} \cdot \text{sq ft} \cdot ^\circ\text{F})$$

### Overall Heat Transfer Coefficient

So far, only the individual or local heat transfer coefficients have been considered. As discussed in Section 9 “Shell and Tube Heat Exchangers” the individual heat transfer coefficients are combined into an overall heat transfer coefficient. See Fig. 9-3 for calculation of  $\Delta T_{\text{LM}}$ .

FIG. 8-5

Heat Transfer Constants for Equation 8-8<sup>2,3</sup> Forced Convection

| Configuration                       | Characteristic Length           | Re                              | Pr                      | C      | m    |
|-------------------------------------|---------------------------------|---------------------------------|-------------------------|--------|------|
| Flat plate parallel to flow         | Plate length                    | $10^3 < \text{Re} < 10^5$       | $> 0.6$                 | 0.648  | 0.50 |
| Cylinder axis perpendicular to flow | Cylinder diameter               | $1 < \text{Re} < 4$             | $> 0.6$                 | 0.99   | 0.33 |
|                                     |                                 | $4 < \text{Re} < 40$            | $> 0.6$                 | 0.91   | 0.39 |
|                                     |                                 | $40 < \text{Re} < 4000$         | $> 0.6$                 | 0.68   | 0.47 |
|                                     |                                 | $4(10)^3 < \text{Re} < 4(10)^4$ | $> 0.6$                 | 0.193  | 0.62 |
|                                     |                                 | $4(10)^4 < \text{Re}$           | $> 0.6$                 | 0.0266 | 0.81 |
| Inside pipes                        | Inside pipe diameter            | $10^4 < \text{Re}$              | $0.7 < \text{Pr} < 700$ | 0.023  | 0.80 |
| Outside bank of tubes               | Staggered outside tube diameter | $2(10)^3 < \text{Re}$           | $> 0.6$                 | 0.33   | 0.60 |
|                                     | In line                         | $2(10)^3 < \text{Re}$           | $> 0.6$                 | 0.26   | 0.60 |

$$Q = U \cdot A \cdot \Delta T_{LM} \quad \text{Eq 8-10}$$

U must be based on some specific area. Considering all the resistances to radial heat transfer through a hollow cylinder whose wall is made of two different materials (i.e. metal pipe and a layer of insulation), the overall heat transfer based on the insulation outside diameter is:

$$U_o = \frac{1}{\frac{1}{h_o} + \frac{D_o}{D_i \cdot h_i} + \frac{D_o \cdot \ln(D_o/D_m)}{2 \cdot k_o} + \frac{D_o \cdot \ln(D_m/D_i)}{2 \cdot k_i} + r f_o + r f_i \cdot \frac{D_o}{D_i}}$$

$$= \frac{1}{\frac{1}{h_o} + \frac{d_o}{d_i \cdot h_i} + \frac{d_o \cdot \ln(d_o/d_m)}{24 \cdot k_o} + \frac{d_o \cdot \ln(d_m/d_i)}{24 \cdot k_i} + r f_o + r f_i \cdot \frac{d_o}{d_i}}$$

Eq 8-11

When there is only one solid layer, delete the fourth term in Equation 8-11 and change the subscript m to i and delete the subscript on k in the third term.

**Example 8-4** — Find the overall heat transfer coefficient for a 3 in. Sch 80 pipe submerged in a 190°F water bath. 10 MMscfd of 2000 psia natural gas is to be heated from 60 to 84°F. Refer to Examples 8-2 and 8-3; note that the heat flow through the pipe wall is similar to Example 8-1.

#### Solution Steps

Use  $h_i$ ,  $h_o$ , and the conduction through the pipe wall to find  $U_o$ . Then check the heat fluxes to see that the right film temperatures were used.  $k = 26.2 \text{ Btu}/[(\text{hr} \cdot \text{sq ft} \cdot ^\circ\text{F})/\text{ft}]$  for the pipe wall at 109°F (value from Fig. 8-8). Assume clean pipe.

From Equation 8-11

$$U_o = \frac{1}{\left[ \frac{1}{122.6} + \left( \frac{3.50}{2.90 (349.9)} \right) + \frac{3.50 \cdot \ln(3.50 / 2.90)}{24 (26.2)} \right]}$$

$$U_o = 79.0 \text{ Btu} / (\text{hr} \cdot \text{sq ft} \cdot ^\circ\text{F})$$

$$Q = U_o A_o \Delta T_{LM} = 79.0 \left( \pi \frac{3.5}{12} \right) \frac{(190 - 60) - (190 - 84)}{\ln \left( \frac{130}{106} \right)}$$

$$= 8516 \text{ Btu} / \text{hr per linear ft}$$

To confirm the film temperatures and the validity of the individual heat transfer coefficients, the heat fluxes outside, through, and inside the pipe must be compared with the overall heat flux. Consider one linear foot of pipe. At the average gas temperature of 72°F, calculate the fluxes for one linear foot of pipe.

$$Q_o = h_o A_i \Delta T_o = (122.6) \left( \pi \frac{3.5}{12} \right) (190 - 114)$$

$$= 8538 \text{ Btu} / \text{hr per linear ft}$$

$$Q_p = \frac{2 \cdot \pi \cdot L \cdot k \cdot \Delta T}{\ln(d_o / d_i)} = \frac{(2) (3.14) (1) (26.2) (114 - 104)}{\ln(3.50 / 2.90)}$$

$$= 8749 \text{ Btu} / \text{hr per linear ft}$$

$$Q_i = h_i A_i \Delta T_i = (350.1) \left( \pi \frac{2.9}{12} \right) (104 - 72)$$

$$= 8506 \text{ Btu} / \text{hr per linear ft}$$

The agreement is close enough for purposes of this example.

The above refers to clean pipes. Fouling occurs with continued use. Sometimes, fouling factors are specified, e.g., 0.001 internally and externally. These are corrections that are added to  $1/U_o$ . So,

$$1 / U_o = 0.01265 + 0.001 + \left( \frac{3.50}{2.90} \right) (0.001)$$

$$U_o = 67.3 \text{ Btu} / (\text{hr} \cdot \text{sq ft} \cdot ^\circ\text{F})$$

#### Finned Tubes

When combustion gases flow externally and heat a liquid in a pipe, there is a significant disparity between  $h_i$  (usually over 150 Btu/[hr · sq ft · °F]) and  $h_o$  (usually less than 10 Btu/[hr · sq ft · °F]). To overcome this and make better use of a given length of pipe, the external surface is finned. When the gas flow is normal to the pipe axis, helical fins (typically 0.05 to 0.105 in. thick, 0.5 to 1.5 in. high, and 24 to 72 fins/ft) are used. The result is an increase of up to tenfold in the external area of the pipe.

The total external surface area of a finned pipe and the cross sectional or projected area restricting normal gas flow per linear foot are:

$$A_o = \frac{\pi \cdot d_o}{12} (1 - n \cdot t / 12) + \left( \frac{n \cdot \pi}{2} \right) \left( \frac{(d_f^2 - d_o^2)}{144} \right) \quad \text{Eq 8-12}$$

and

$$A_{cs} = \frac{d_o}{12} + \frac{n \cdot t (d_f - d_o)}{144} \quad \text{Eq 8-13}$$

The surface area of the fins is not as efficient as the external surface of the pipe because heat absorbed at the fin surface must be conducted to the fin base before it can pass through the pipe wall. Fin efficiencies are given in Fig. 8-6. These efficiencies are applied to the total external area.

Another important consideration is fin tip temperature. This can be obtained from the fin efficiency and Fig. 8-7. Fig. 8-8 gives the thermal conductivities and maximum recommended fin tip temperatures for the more common ferrous construction materials.

**Example 8-5** — Calculate the external surface area and fin efficiency for 4 in. Sch 80 pipe with the following finning: 36 fins/ft, 1.25 in. high, 0.105 in. thick. Assume  $h_o = 3.9 \text{ Btu}/(\text{hr} \cdot \text{sq ft} \cdot ^\circ\text{F})$ ,  $k_f = 25 \text{ Btu}/[(\text{hr} \cdot \text{sq ft} \cdot ^\circ\text{F})/\text{ft}]$ .

#### Solution Steps

Abscissa in Fig. 8-6:

$$0.4 H_f \sqrt{\frac{h_o}{k_f t}} = 0.4 (1.25) \sqrt{\frac{39}{(25) (0.105)}} = 0.61$$

$$d_f = d_o + 2 H_f = 4.5 + 2 (1.25) = 7.0 \text{ in.}$$

$$\frac{d_f}{d_o} = \frac{7.0}{4.5} = 1.5$$

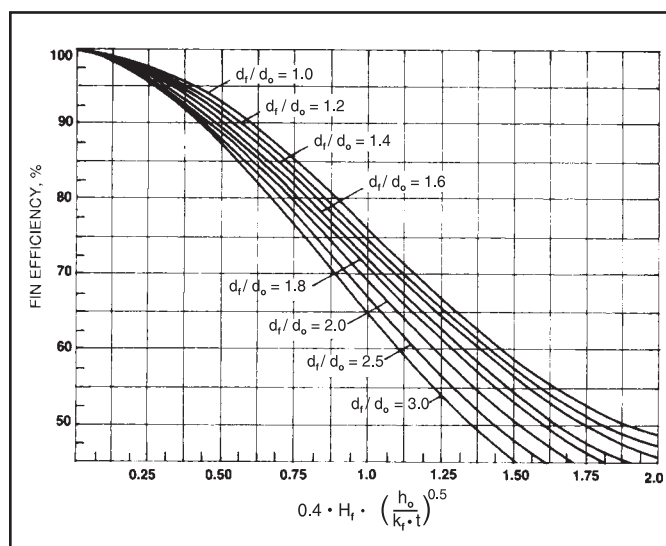
From Fig. 8-6, fin efficiency is 87%.

From Equation 8-12:

$$A_o = \pi \left( \frac{4.5}{12} \right) \left( 1 - \frac{(36) (0.105)}{12} \right) + \frac{36}{2} \pi \left( \frac{7.0^2 - 4.5^2}{144} \right)$$

$$= 12.10 \text{ sq ft per linear ft}$$

**FIG. 8-6**  
**Fin Efficiency Chart<sup>4</sup>**



## Radiation

An estimate of the radiant heat flux between two surfaces is:

$$\frac{Q}{A} = \frac{\sigma \cdot F (T_1^4 - T_2^4)}{(1/\varepsilon_1 + 1/\varepsilon_2 - 1)} \quad \text{Eq 8-14}$$

The geometric or view factor,  $F$ , is the fraction of the surface area that is exposed to and absorbs radiant heat. The equation for  $F$  must be determined from an analysis of the geometry. In using Equation 8-14, it is recommended<sup>6</sup> that  $F$  not be less than 0.67. Also, all temperatures are absolute.

Fig. 8-9 gives the emissivities of common construction metals, oxides, refractories, and insulation materials. The emissivity of combustion gases is more complex because it depends on the temperature and the product ( $P \cdot L$ ). See Figs. 8-10, 8-11, and 8-12.

**Example 8-6** — What is the radiant heat flux to a 3 ft length of a 2 ft ID firetube when the combustion gases inside the tube are at 2800°F and the firetube wall is at 300°F? Assume 20% excess air is used.

### Solution Steps

$$F = \frac{\text{curved surface area}}{\text{total surface area}} = \frac{\pi \cdot D \cdot L}{\pi \cdot D \cdot L + 2(\pi \cdot D^2 / 4)}$$

$$= \frac{2(3)}{2(3) + 2(4/4)} = 0.75$$

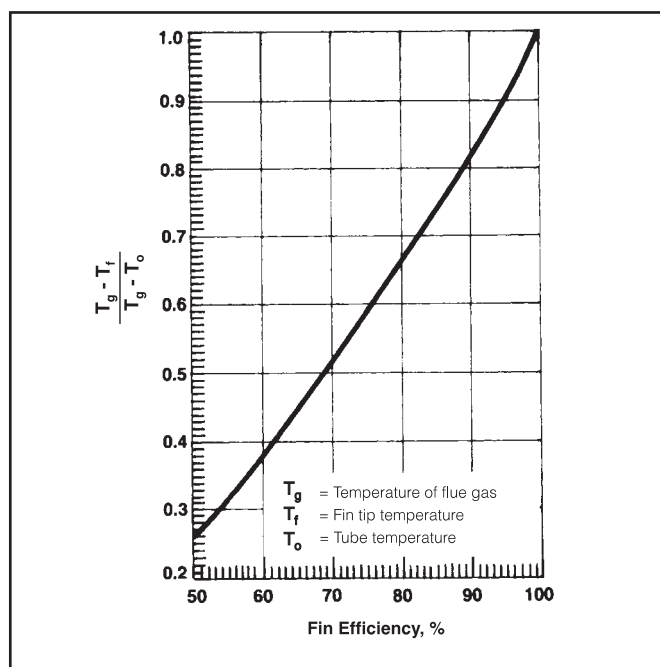
From Fig. 8-10,  $P_{CO_2} + P_{H_2O} = 0.24$

From Fig. 8-11,  $L = 2.0$  ft, so  $P \cdot L = 0.48$

From Fig. 8-12,  $\varepsilon_1 = 0.12$

From Fig. 8-9,  $\varepsilon_2 = 0.79$  (steel, oxidized at 1100°F)

**FIG. 8-7**  
**Fin Tip Temperature<sup>5</sup>**



Equation 8-14,  $\frac{Q}{A} = \frac{0.73 (10^{-8}) 0.75 (3260^4 - 760^4)}{(1/0.12 + 1/0.79 - 1)}$

$$= 16,990 \text{ Btu / (hr} \cdot \text{sq ft)}$$

Note that  $T$  is in °R.

## Heat Losses

Heat losses from equipment surfaces occur primarily by radiation and convection. Fig. 8-13 gives the combined heat transfer coefficient,  $h_c + h_r$ , in terms of the wind velocity and the temperature difference between the surface and the surrounding air.

**Example 8-7** — How much heat can be saved per linear foot by covering an 8 in. Sch 40 steam header, carrying 15 psig steam at 250°F, with a 1 in. thick layer of block insulation? Assume ambient conditions are 30°F with a 15 mph wind.

### Solution Steps

Using Fig. 8-13 the heat loss from the bare pipe is:

$$Q = (h_c + h_r) A_o (T_p - T_a) = (5.85) \left(\frac{\pi 8.625}{12}\right) (250 - 30)$$

$$= 2906 \text{ Btu / hr per linear ft}$$

For the insulated pipe, assume the outside surface of the insulation is at 50°F. Then from Fig. 8-13:

$$h_c + h_r = 4.5 \text{ Btu / (hr} \cdot \text{sq ft} \cdot ^\circ\text{F)}$$

$$Q = (4.5) \left(\frac{\pi 10.625}{12}\right) (50 - 30) = 250 \text{ Btu / hr per linear ft}$$

FIG. 8-8  
Thermal Conductivity of Ferrous Materials<sup>4</sup>

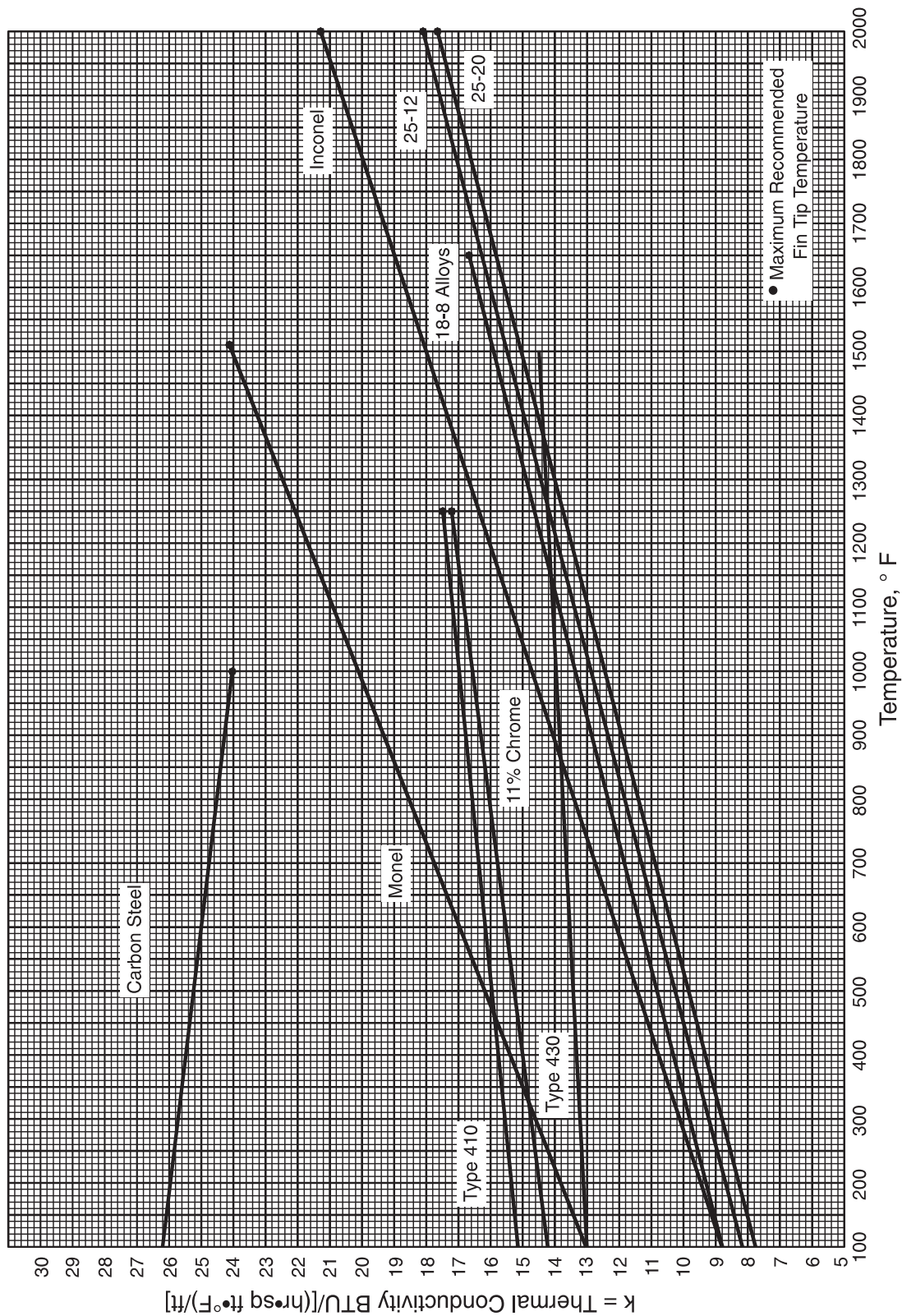


**FIG. 8-9**  
**Normal Total Emissivity of Various Surfaces<sup>3</sup>**

**A. Metals and Their Oxides**

| Surface                                                                            | T, °F*    | Emissivity*   |
|------------------------------------------------------------------------------------|-----------|---------------|
| Aluminum                                                                           |           |               |
| Highly polished plate, 98.3% pure                                                  | 440-1070  | 0.039-0.057   |
| Polished plate                                                                     | 73        | 0.040         |
| Rough plate                                                                        | 78        | 0.055         |
| Oxidized at 1110°F                                                                 | 390-1110  | 0.11-0.19     |
| Aluminum-surfaced roofing                                                          | 100       | 0.216         |
| Calorized surfaces, heated at 1110°F:                                              |           |               |
| Copper                                                                             | 390-1110  | 0.18-0.19     |
| Steel                                                                              | 390-1110  | 0.52-0.57     |
| Brass                                                                              |           |               |
| Highly polished:                                                                   |           |               |
| 73.2% Cu, 26.7% Zn                                                                 | 476-674   | 0.028-0.031   |
| 62.4% Cu, 36.8% Zn, 0.4% Pb, 0.3% Al                                               | 494-710   | 0.033-0.037   |
| 82.9% Cu, 17.0% Zn                                                                 | 530       | 0.030         |
| Chromium; (see Nickel Alloys for Ni-Cr steels)                                     | 100-1000  | 0.08-0.26     |
| Copper                                                                             |           |               |
| Commercial, emiered, polished, but pits remaining                                  | 66        | 0.030         |
| Commercial, scraped shiny but not mirror-like                                      | 72        | 0.072         |
| Polished                                                                           | 242       | 0.023         |
| Plate, heated long time, covered with thick oxide layer                            | 77        | 0.78          |
| Cuprous oxide                                                                      | 1470-2010 | 0.66-0.54     |
| Iron and steel                                                                     |           |               |
| Metallic surfaces (or very thin oxide layer):                                      |           |               |
| Cast iron, polished                                                                | 392       | 0.21          |
| Ground sheet steel                                                                 | 1720-2010 | 0.55-0.61     |
| Smooth sheet iron                                                                  | 1650-1900 | 0.55-0.60     |
| Oxidized surfaces:                                                                 |           |               |
| Iron plate, pickled, then rusted red                                               | 68        | 0.612         |
| Completely rusted                                                                  | 67        | 0.685         |
| Rolled sheet steel                                                                 | 70        | 0.657         |
| Oxidized iron                                                                      | 212       | 0.736         |
| Cast iron, oxidized at 1100°F                                                      | 390-1110  | 0.64-0.78     |
| Steel, oxidized at 1100°F                                                          | 390-1110  | 0.79          |
| Iron oxide                                                                         | 930-2190  | 0.85-0.89     |
| Sheet steel, strong rough oxide layer                                              | 75        | 0.80          |
| Dense shiny oxide layer                                                            | 75        | 0.82          |
| Cast plate:                                                                        |           |               |
| Smooth                                                                             | 73        | 0.80          |
| Rough                                                                              | 73        | 0.82          |
| Cast iron, rough, strongly oxidized                                                | 100-480   | 0.95          |
| Wrought iron, dull oxidized                                                        | 70-680    | 0.94          |
| Steel plate, rough                                                                 | 100-700   | 0.94-0.97     |
| High temperature alloy steels (see Nickel Alloys)                                  |           |               |
| Monel metal, oxidized at 1110°F                                                    | 390-1110  | 0.41-0.46     |
| Nickel                                                                             |           |               |
| Electroplated on pickled iron, not polished                                        | 68        | 0.11          |
| Plate, oxidized by heating at 1110°F                                               | 390-1110  | 0.37-0.48     |
| Nickel oxide                                                                       | 1200-2290 | 0.59-0.86     |
| Nickel alloys                                                                      |           |               |
| Chromnickel                                                                        | 125-1894  | 0.64-0.76     |
| Nickelin (18-32 Ni; 55-68 Cu; 20 Zn), gray oxidized                                | 70        | 0.262         |
| KA-2S alloy steel — (8% Ni; 18% Cr), light silvery, rough, brown, after heating    | 420-914   | 0.44-0.36     |
| After 42 hr. heating at 980°F                                                      | 420-980   | 0.62-0.73     |
| NCT-3 alloy (20% Ni; 25% Cr), brown, splotted, oxidized from service               | 420-980   | 0.90-0.97     |
| NCT-6 alloy (60% Ni; 12% Cr), smooth, black, firm adhesive oxide coat from service | 520-1045  | 0.89-0.82     |
| Tin — bright tinned iron sheet                                                     | 76        | 0.043 & 0.064 |
| Zinc                                                                               |           |               |
| Commercial, 99.1% pure, polished                                                   | 440-620   | 0.045-0.053   |
| Oxidized by heating at 750°F                                                       | 750       | 0.11          |
| Galvanized sheet iron, fairly bright                                               | 82        | 0.228         |
| Galvanized sheet iron, gray oxidized                                               | 75        | 0.276         |

**B. Refractories, Building Materials, Paints, and Miscellaneous**

| Surface                                                                                                                   | T, °F*    | Emissivity* |
|---------------------------------------------------------------------------------------------------------------------------|-----------|-------------|
| Asbestos                                                                                                                  |           |             |
| Board                                                                                                                     | 74        | 0.96        |
| Paper                                                                                                                     | 100-700   | 0.93-0.945  |
| Brick                                                                                                                     |           |             |
| Red, rough, but no gross irregularities                                                                                   | 70        | 0.93        |
| Silica, unglazed, rough                                                                                                   | 1832      | 0.80        |
| Silica, glazed, rough                                                                                                     | 2012      | 0.85        |
| Grog brick, glazed                                                                                                        | 2012      | 0.75        |
| See Refractory Materials below.                                                                                           |           |             |
| Carbon                                                                                                                    |           |             |
| T-carbon (Gebr. Siemens) 0.9% ash (this started with emissivity at 260°F of 0.72, but on heating changed to values given) | 260-1160  | 0.81-0.79   |
| Enamel, white fused, on iron                                                                                              | 66        | 0.897       |
| Glass, smooth                                                                                                             | 72        | 0.937       |
| Gypsum, 0.02 in. thick on smooth or blackened plate                                                                       | 70        | 0.903       |
| Marble, light gray, polished                                                                                              | 72        | 0.931       |
| Oak, planed                                                                                                               | 70        | 0.895       |
| Oil layers on polished nickel (lube oil)                                                                                  | 68        |             |
| Polished surface, alone                                                                                                   |           | 0.045       |
| +0.001-in. oil                                                                                                            |           | 0.27        |
| +0.002-in. oil                                                                                                            |           | 0.46        |
| +0.005-in. oil                                                                                                            |           | 0.72        |
| Infinitely thick oil layer                                                                                                |           | 0.82        |
| Oil layers on aluminum foil (linseed oil)                                                                                 |           |             |
| Al foil                                                                                                                   | 212       | 0.087†      |
| +1 coat oil                                                                                                               | 212       | 0.561       |
| +2 coats oil                                                                                                              | 212       | 0.574       |
| Paints, lacquers, varnishes                                                                                               |           |             |
| Snowwhite enamel varnish on rough iron plate                                                                              | 73        | 0.906       |
| Black shiny lacquer, sprayed on iron                                                                                      | 76        | 0.875       |
| Black shiny shellac on tinned iron sheet                                                                                  | 70        | 0.821       |
| Black matte shellac                                                                                                       | 170-295   | 0.91        |
| Black lacquer                                                                                                             | 100-200   | 0.80-0.95   |
| Flat black lacquer                                                                                                        | 100-200   | 0.96-0.98   |
| White lacquer                                                                                                             | 100-200   | 0.80-0.95   |
| Oil paints, sixteen different, all colors                                                                                 | 212       | 0.92-0.96   |
| Aluminum paints and lacquers                                                                                              |           |             |
| 10% Al, 22% lacquer body, on rough or smooth surface                                                                      | 212       | 0.52        |
| 26% Al, 27% lacquer body, on rough or smooth surface                                                                      | 212       | 0.3         |
| Other Al paints, varying age and Al content                                                                               | 212       | 0.27-0.67   |
| Al lacquer, varnish binder, on rough plate                                                                                | 70        | 0.39        |
| Al paint, after heating to 620°F                                                                                          | 300-600   | 0.35        |
| Plaster, rough lime                                                                                                       | 50-190    | 0.91        |
| Porcelain, glazed                                                                                                         | 72        | 0.924       |
| Quartz, rough, fused                                                                                                      | 70        | 0.932       |
| Refractory materials, 40 different poor radiators                                                                         | 1110-1830 | 0.65-0.75   |
| good radiators                                                                                                            |           | 0.70        |
|                                                                                                                           |           | 0.80-0.85   |
|                                                                                                                           |           | 0.85-0.90   |
|                                                                                                                           |           | 0.91        |
| Roofing paper                                                                                                             | 69        |             |
| Rubber                                                                                                                    |           |             |
| Hard, glossy plate                                                                                                        | 74        | 0.945       |
| Soft, gray, rough (reclaimed)                                                                                             | 76        | 0.859       |
| Water                                                                                                                     | 32-212    | 0.95-0.963  |

\* When two temperatures and two emissivities are given, they correspond, first to first and second to second, and linear interpolation is permissible.

† Although this value is probably high, it is given for comparison with the data, by the same investigator, to show the effect of oil layers. See Aluminum, part A of this table.

This agrees closely enough with the heat flow through the insulation — Example 8-1.

Heat saved = 2906 – 250 = 2656 Btu/hr per linear ft

## COMBUSTION

Combustion is the rapid chemical reaction between oxygen and a combustible material that releases heat and light. Usually the combustible material is a hydrocarbon and ambient air supplies the oxygen. Complete combustion occurs when there is sufficient oxygen to convert all of the carbon to carbon dioxide and all of the hydrogen to water. Incomplete combustion means that there is either unburned or partially reacted fuel, i.e., carbon monoxide, hydrogen, etc.

Methane is the main constituent of natural gas. It reacts with oxygen to form carbon dioxide and water.



FIG. 8-10  
Partial Pressure of CO<sub>2</sub> Plus H<sub>2</sub>O

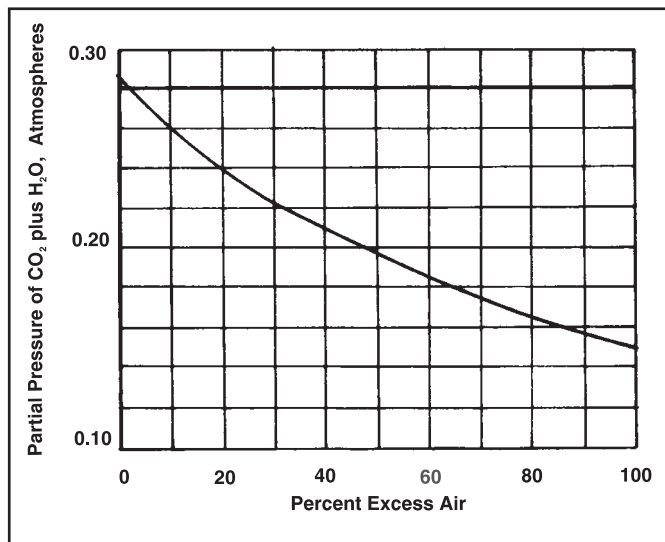


FIG. 8-11  
Beam Length for Gas Radiation<sup>8</sup>

| Dimension Ratio                                               | Mean Beam Length, L                   |
|---------------------------------------------------------------|---------------------------------------|
| Rectangular Furnaces,<br>Length-Width-Height,<br>In Any Order |                                       |
| 1-1-1 to 1-1-3 }<br>1-2-1 to 1-2-4 }                          | (2/3) (Furnace Volume) <sup>1/3</sup> |
| 1-1-4 to 1-1-∞                                                | (1) (Smallest Dimension)              |
| 1-2-5 to 1-2-∞                                                | (1.3) (Smallest Dimension)            |
| 1-3-3 to 1-∞-∞                                                | (1.8) (Smallest Dimension)            |
| Cylindrical Furnaces,<br>Diameter-Height                      |                                       |
| 1-1                                                           | (2/3) (Diameter)                      |
| 1-2 to 1-∞                                                    | (1) (Diameter)                        |

FIG. 8-12  
Gas Emissivity<sup>10</sup>

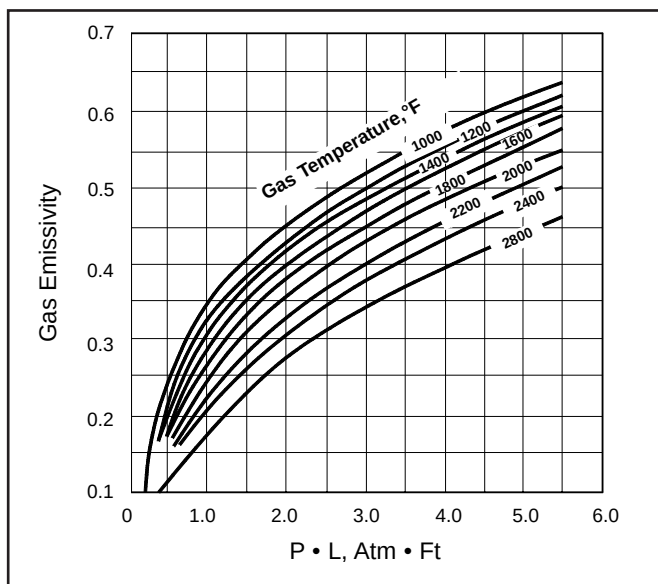
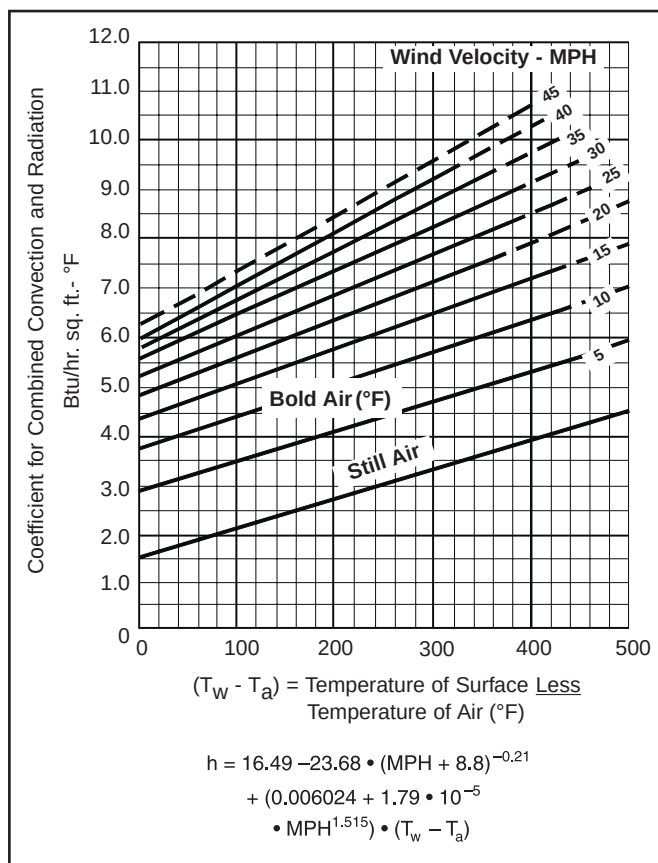


FIG. 8-13  
Combination Convection and Radiation Film Coefficients  
for Air in Contact with Vertical Walls or Surfaces<sup>11</sup>



This stoichiometry is typical of all hydrocarbons. One atom of carbon requires one molecule of oxygen and four atoms of hydrogen require one molecule of oxygen. The theoretical air is that needed for complete combustion of the carbon and hydrogen, i.e., two molecules of oxygen for one molecule of methane. Excess air is that supplied in addition to what is required. For example, 20% excess air means that the air supplied is 1.2 times the stoichiometric amount.

The following reaction represents the complete combustion in oxygen of an arbitrary carbon-based fuel compound. For combustion in air, add  $N_2$  to both sides of the reaction equation in an amount equal to the oxygen input multiplied by 3.774.

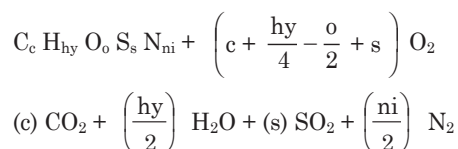


Fig. 8-14 shows how the composition of the flue gases depends on the amount of combustion air.

## Air Requirements

Fig. 8-15a shows the scf of dry air needed per scf of paraffinic hydrocarbons for complete combustion in terms of the specific gravity of the fuel. In using this figure any inert components in the fuel, e.g., nitrogen, carbon dioxide, etc., must be excluded. Fig. 8-15b shows the mass of humid air required per mass of dry air at 760 mm Hg and percent relative humidity.

Air is about 20.9% oxygen on a dry basis, hence 4.77 mols (or scf) of air supply 1.0 mol (or scf) of oxygen. Applying this to methane, 9.54 mol (or scf) of air are needed for every mol (or scf) of methane.

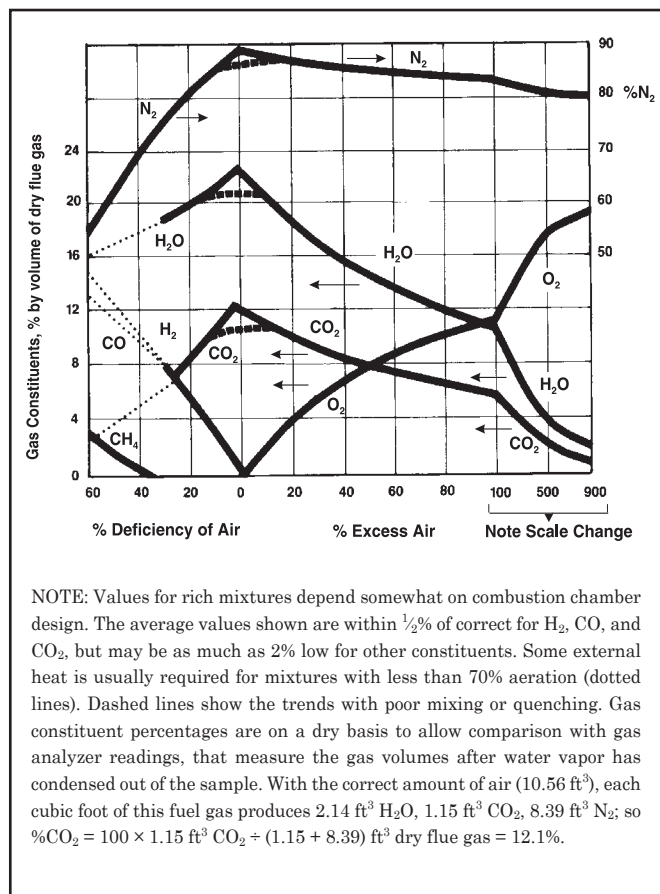
The effect of water vapor in the air is relatively small at low and moderate temperatures. Saturated air at 60°F contains 1.75% water. Still this should be considered and 2-3% more air is usually added if exact calculations are not made. The water content in saturated air increases rapidly with temperature; e.g. at 100°F saturated air contains about 6.5% water, and at 115°F it contains about 10%.

Some situations may yield a higher amount of water vapor coming from the combustion air and fuel gas. Consider the complete combustion of 1 mol of water saturated methane at 100°F and 15 psig with 20% excess air with air also water saturated at 100°F. This situation introduces 0.79 mol of water from the air and 0.032 mol of water from the gas. Additionally, 2 mols of water from the methane combustion is added water resulting in approximately 21% water in the flue gas of which 30% is from the air and gas humidity. Also, steam or water addition for  $NO_x$  control introduces more water vapor to the flue gas. These situations increase the wet bulb temperature of the flue gas. Water condensation should be considered in mass and energy balances and excess air calculations. Errors in consideration of water vapor content and air temperature may cancel a 10% excess air calculation, resulting in incomplete fuel combustion. Designs and operations should consider local weather conditions and seasonal changes.

The theoretical air requirement of an arbitrary carbon-based fuel compound, in mols of dry air per mol of fuel, can be calculated with the following equation.

$$AO = 4.77 \cdot \left[ c + \frac{hy}{4} - \frac{o}{2} + s \right] \quad \text{Eq 8-15}$$

**FIG. 8-14**  
Effect of Fuel/Air Ratio on Flue Gas Analysis  
for 1108 Btu/SCF Natural Gas (0.63 Gas Gravity)  
Containing 83%  $CH_4$  and 16%  $C_2H_6$ <sup>1</sup>



Analysis of the flue gases provides useful information about the actual excess air and the efficiency of fired equipment. The following equations provide the excess air percentage for a sulfur and oxygen free, carbon-based fuel combustion without soot formation. Analysis must be molar and on a dry basis.

$$EA = \frac{Fl_o}{AO} \left[ \frac{CO_{2o}}{CO_2 + CO} \right] \cdot 100$$

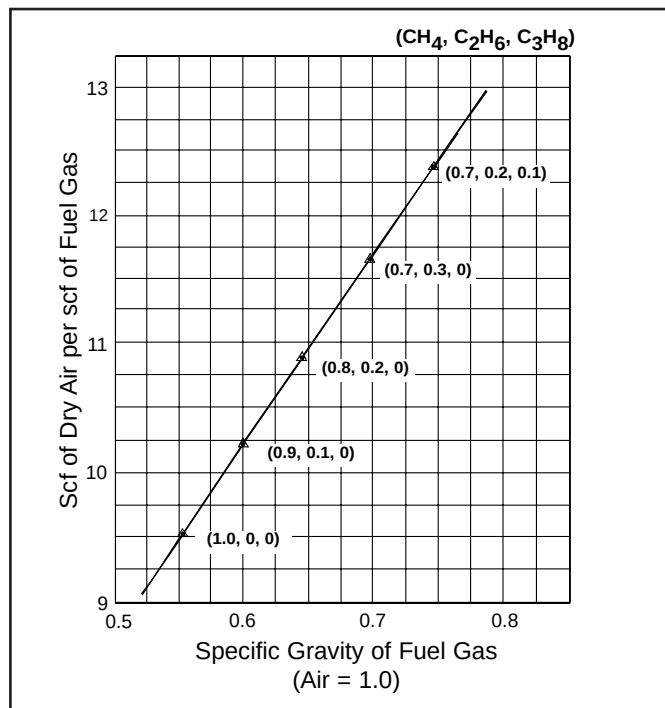
$$= \frac{Fl_o}{AO} \left[ \frac{O_{2o}}{20.9 - O_2 + CO} \right] \cdot 100 \quad \text{Eq 8-16}$$

Many forced-draft burners supply a fixed volume of air. Fig. 8-18 shows the effect of ambient temperature and barometric pressure on the amount of air actually delivered.

The air ideal density and ideal relative density changes with the humidity. For the same relative humidity, the hotter the air, the higher the influence of the humidity in the air densities, because of the higher water vapor fraction, as can be seen in Fig. 8-16 and Fig. 8-17. In these graphs the atmosphere pressure is 760 mm Hg; for other conditions use the equation shown in the graph.

FIG. 8-15a

Standard Cubic Feet of Dry Air Needed per Standard Cubic Foot of Hydrocarbon for Complete Combustion



## Heating Value

The heating value is the amount of ideal heat released by a unit of fuel, mass or standard volume, during complete combustion, at constant pressure, with the stoichiometric amount of dry air. The fuel humidity must be stated, as well as whether the gas volume is real or ideal. This involves a heat balance at standard conditions of temperature and pressure, (usually 60°F [15°C] and 760 mm Hg).

Hydrogen in the fuel burns to water and when the flue gases are cooled to 60°F, the physical state — either vapor or liquid — of this water must be assumed. So the latent heat of vaporization of the water may or may not be considered to be part of the heating value. The result is two definitions for the heating value. The higher or gross heating value, HHV, includes the heat of condensation and the lower or net heating value, LHV, assumes the water remains in the vapor state.

Fig. 23-2 in the “Physical Properties” section gives the net and gross heating values of most pure hydrocarbons. For mixtures calculate the molar, or volume, average.

The higher, ideal, dry heating value of sweet natural gas at 60°F and 760 mm Hg may be calculated with the following equation:

$$\text{HHV} = 1568.72 \cdot \text{SG} - 2524.88 \cdot X_{\text{CO}_2} - 1658.37 \cdot X_{\text{N}_2} + 141.05 \quad \text{Eq 8-17}$$

Where HHV is in Btu/scf, SG is the ideal relative density, and X is the fraction of carbon dioxide and nitrogen if present.

FIG. 8-15b

Mass of Humid Air Per Mass of Dry Air at 760 mm Hg and Percent Relative Humidity

