Engineering Encyclopedia

Saudi Aramco DeskTop Standards

Furnace and Boiler Design and Operating Parameters

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CALCULATING FURNACE EFFICIENCY

Flammability Limits

Control of furnaces involves control of flammability and combustion to release heat. The limits of flammability were studied in Module 1. The limits of flammability for mixtures are calculated by calculating a volumetric (molar) average flammability limits. Prior to starting a furnace (includes heaters and boilers) the furnace conditions must be below the limit of flammability before flame is introduced into the furnace to avoid explosions. Operation of furnaces requires maintaining furnace conditions within the limits of flammability in order to burn fuel. Figure 1 lists the Lower Explosive Limit (LEL) and the Upper Explosive Limit (UEL) in air which are limits of flammability in air at atmospheric pressure.

Gas or Vapor	LEL	UEL
Hydrogen	4.00	75.0
Carbon Monoxide	12.50	74.0
Ammonia	15.50	26.60
Hydrogen Sulfide	4.30	45.50
Carbon Disulfide	1.25	44.0
Methane	5.30	14.0
Ethane	3.00	12.5
Propane	2.20	9.5
Butane	1.90	8.5
Iso-butane	1.80	8.4
Pentane	1.50	7.80
Iso-pentane	1.40	7.6
Hexane	1.20	7.5
Heptane	1.20	6.7
Octane	1.00	3.20
Nonane	0.83	2.90

Note: More complete tables of data are included in Appendix of “GASEOUS FUELS” published by A.G.A., 1954 (10).

Limits of Flammability of Gases and Vapors, Percent in Air
Figure 1

Heats of Combustion

The heating value of a fuel gas or a flue gas can be calculated from the chemical equations given in Figure 2 and the composition of the gas. The heating value is calculated using the equation and the heats of formation for each chemical species. The heating value of a mixture is determined by calculating the volumetric (mole) average heating value of the mixture if the heating values are in Btu/cf. Use weight average heating values if the heating values are in Btu/lb.

	Heating Value(Btu/lb)	
	HHV	LHV
$H_2 + 1/2\ O_2 = H_20$	61,100	51,600
$C + O_2 = CO_2$	14,093	14,093
$C + 1/2\ O_2 = CO$	4,440	4,440
$CO + 1/2\ O_2 = CO_2$	4,345	4,345
$S + O_2 = SO_2$	10,160	10,160
$CH_4 + 2\ O_2 = CO_2 + 2\ H_2O$	23,885	21,500
$C_2H_6 + 3\ 1/2\ O_2 = 2\ CO_2 + 3\ H_2O$	22,263	20,370
$C_3H_8 + 5\ O_2 = 3\ CO_2 + 4\ H_2O$	21,646	19,929
$C_4H_{10} + 6\ 1/2\ O_2 = 4\ CO_2 + 5\ H_2O$	21,293	19,665

Note that where no water is formed, the HHV and LHV are the same. Using the composition of air as 21% O_2 and 79% N_2, the above equations can be used to calculate the amount of air required for 100% combustion by making a molar material balance.

Combustion Equations
Figure 2

The heat liberated when one pound of fuel at 60°F is burned, and the combustion products are cooled to 60°F is called the lower heating value (LHV) or net heating value. If the water produced by the combustion is condensed, the higher heating value (HHV) or gross heating value is obtained. Since process furnaces do not condense the water of combustion, furnace calculations are performed on a LHV basis. The heating value of a fuel gas can be calculated from its analysis and the component heating values. Typical refinery fuel gas heating values as a function of their molecular weight are given in Maxwell, p. 181. Heating values for typical refinery fuel oils as a function of their API gravity are given in Maxwell, p. 180.

Example Problem 1

Calculate the lower heating value (LHV) of a refining gas which has the following analysis:

		Vol. %
Hydrogen, H_2	=	5.1
Methane, CH_4	=	86.4
Ethane, C_2H_6	=	8.3
Propane, C_3H_8	=	0.2
Total	=	100.0

Answer:

Volume % and molar % are equal for a gas. Use a 100 mole basis.

	Moles	MW	lbs	Wt %	LHV Btu/lb	Wt% x LHV/100
Hydrogen	5.1	2.0	10.2	0.62	51,600	319.9
Methane	86.4	16.0	1382.4	83.72	21,300	17999.8
Ethane	8.3	30.1	249.8	15.13	20,370	3082.0
Propane	0.2	44.1	8.8	0.53	19,929	105.6
Total	100.0	16.51	1651.2	100.00	21,507.3	21507.3

Mixture LHV = 21,507 Btu/lb

Furnaces

All furnaces and heaters are classified in one of two categories; direct fired heaters (flame outside tubes) or fire tube heaters (flame inside tubes). Because most furnaces and heaters in a refinery are direct fired, the following discussion will be limited to direct fired equipment; however, a brief summary of fire tube heater types, their characteristics, and how they compare with direct fired heaters is given below in Figure 3 as general background.

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

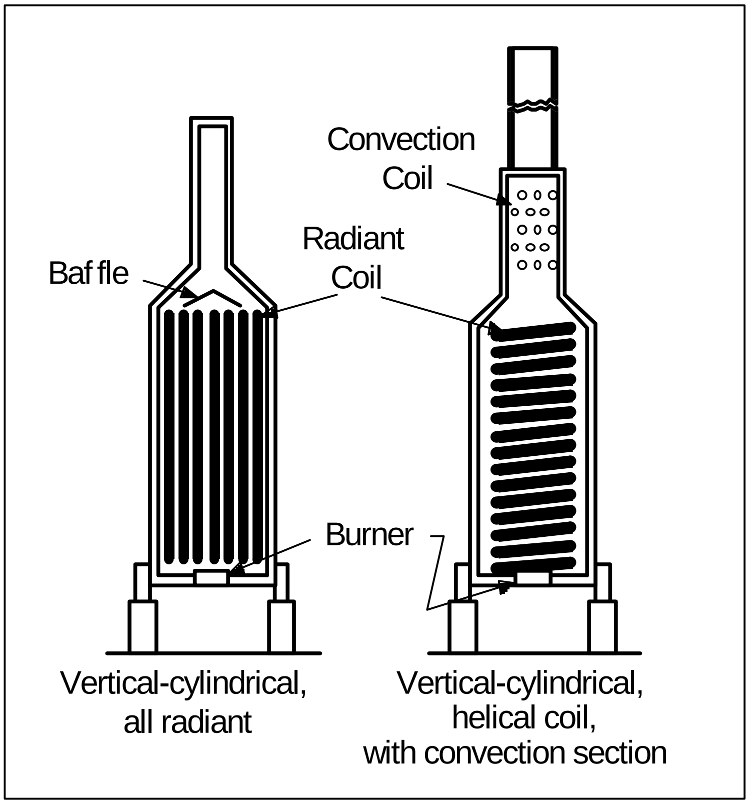
With permission from the Gas Processors Suppliers Association. Source: Engineering Data Book.
MBtu/hr = Million Btu/hr which is usual for heat transfer calculations.

Furnace Categories
Figure 3

Direct Fired

There are two basic types of direct fired furnaces, cylindrical and cabin. Within each type there are many different configurations. The furnaces can have different coil arrangements: horizontal, vertical, helical, or serpentine. Also, the furnace can be all radiant (no convection section) or have a convection section. Several configurations for the vertical cylindrical and cabin type furnaces are shown in Figures 4 and 5.

The all radiant cylindrical furnace is the simplest and least expensive. Typically, an all-radiant furnace operates with about a 60% efficiency and a stack temperature of about 1200°F. Adding a convection section to an all-radiant vertical cylindrical furnace increases the overall furnace efficiency to about 80% and drops the stack temperature to about 750°F. Of course, the convection section significantly increases the furnace cost.



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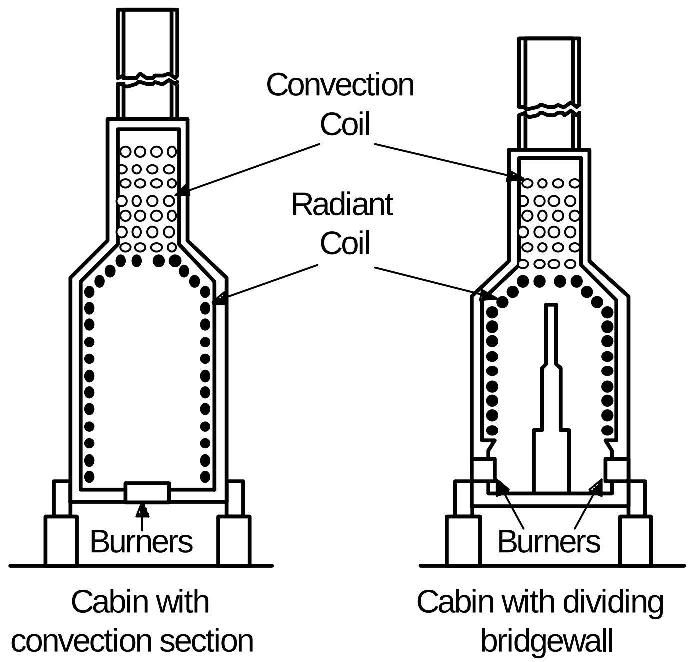
Examples of Vertical Cylindrical Direct Fired Furnaces
Figure 4



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Examples of Cabin Direct Fired Furnaces
Figure 5

Some of the advantages for the two types of direct-fired furnaces are identified below in Figure 6.

Cylindrical Furnace Advantages:

- Require the smallest plot area for a given duty.
- The cost is usually 10 to 15% lower in the larger sizes.
- Can accommodate more parallel passes in the process coil.
- For large duties, a cylindrical heater has a taller firebox and more natural draft at the burner.
- The flue gas velocity is usually higher in the convection section, hence, the flue gas film coefficient is higher.
- Few expensive tube supports or guides are required in the convection section.
- The noise plenums or preheated combustion air plenums are smaller.
- Fewer soot blowers are required in the convection section. (Soot blowers are not needed for gaseous fuel.)
- If coil drainage is a problem (vertical tubes), a helical coil may be used when there is only one pass.

Cabin Furnace Advantages

- The process coil can always be drained.
- Two-phase flow problems are less severe (slug flow can generally be avoided).
- Cabins can accommodate side-firing or end-firing burners instead of only vertically upward firing. This permits the floor of the heater to be closer to the ground. (Some burner manufacturers prefer to fire liquid fuels horizontally.)

With permission from the Gas Processors Suppliers Association. Source: Engineering Data Book.

Comparison of Cylindrical and Cabin Furnaces

Figure 6

The major components of a furnace are the radiant section (firebox), convection section, stack, burner fuel system, and process fluid coil. The radiant section provides the high level heat to the process coil, with the process fluid flow leaving the furnace via the radiant section. The burner flame is contained in the radiant section. The combustion gases leaving the radiant section typically are in the 1500-1900°F temperature range. Heat is transferred from the flame to the process coil mainly by radiation from the flame.

The hot gases of combustion leave the radiant section and flow into the convection section, which transfers the lower-level heat to the cold process fluid as it enters the furnace. The combustion gases are cooled in the convection section from the 1500-1900°F range to less than 750°F. Heat is transferred from the gases of combustion (flue gas) to the process fluid coil via convection (hot gas moving over pipes).

The stack sits on top of the convection section and generates sufficient driving force to overcome the friction losses of the hot flue gas flowing over the convection section tubes. If pollution considerations set the stack height higher than is needed, a damper in the stack can absorb the incremental available draft. Refer to Figure 9 for an illustration of draft in a natural draft furnace.

The burner/fuel system includes the burner, which mixes air with fuel and burns the fuel in the radiant section of the furnace. The burner flame typically is about 60% of the height of the radiant section. Fuel and air are fed to the burner by separate pipe/duct systems.

The process fluid coil carries the process fluid being heated in the furnace from the process inlet in the convection section (flue gas outlet) to the process outlet in the floor of the radiant section. The coil changes in configuration (horizontal, vertical, bare tube, finned tube) and type of materials throughout the furnace. The coil is exposed to relatively mild conditions at the process inlet in the convection section and to severe conditions in the radiant section.

Excess Oxygen/Excess Air

Any amount of oxygen (air) in excess of that required to achieve full combustion is termed excess oxygen (excess air). All furnaces require some excess oxygen to ensure complete combustion. Typically these run about 20% excess oxygen (excess air) for gas fired furnaces depending on burner selection and 30% excess oxygen (excess air) for oil fired furnaces. All air entering the furnace in excess of that required for complete combustion will lower furnace efficiency, since it must be heated from ambient temperature conditions to the stack temperature. Therefore, efforts are made to reduce excess air to a minimum, while still maintaining stable furnace operation.

Efficiency calculations for an operating furnace begin with the determination of excess oxygen. The method is shown in Figure 7 and is detailed in Example Problem 1.

1. Obtain flue gas analyses CO_2, CO, O_2, N_2.
2. From the percent N_2, calculate the total O_2 into the furnace.
3. Reduce the free O_2 by the amount required to burn the CO to CO_2.
   The remaining free O_2 is excess. (CO is usually negligible)
4. O_2 required = (total in) less (excess)
5. $$\text{Percent excess } O_2 = \frac{(\text{excess } O_2)}{(\text{required } O_2)} \times 100 = \frac{(\text{excess})}{(\text{total - excess})} \times 100$$

Excess Oxygen
Figure 7

Example Problem 2

Calculation Of Excess Oxygen

Flue gas analysis:	CO_2	9.5
	CO	1.8
	O_2	2.0
	N_2	86.7
		100.0

Air composition: 21% O_2, 79% N_2

$$O_2 \text{ into furnace} = 86.7 \times \frac{0.21}{0.79} = 23.0 \text{ moles/100 moles flue gas}$$

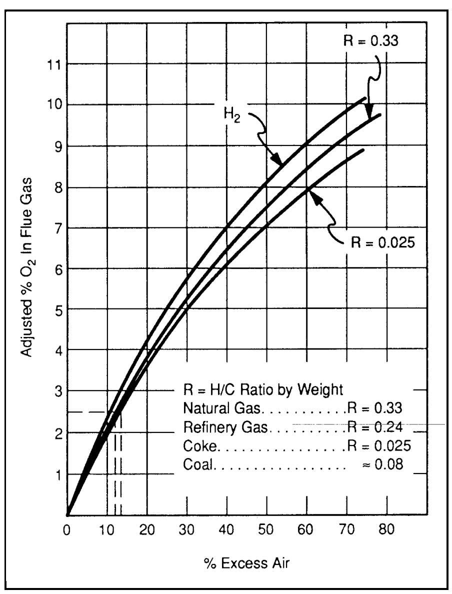
$$1.8\ CO + 0.9\ O_2 \rightarrow 1.8\ CO_2$$

(Note: Usually CO is in parts per million and this correction can be ignored)

$$\text{Net } O_2 = 2.0 - 0.9 = 1.1 \text{ moles/100 moles flue gas}$$

$$\text{Percent excess } O_2 = \frac{1.1}{(23 - 1.1)} \times 100 = 5.02\%$$

Figure 8 (Work Aid 2) can also be used to calculate excess air (oxygen) once the oxygen has been adjusted for complete combustion. For 1.1% O_2 Figure 8 gives an excess air of 5%. **Excess air and excess oxygen are numerically equal**, because both numerator and denominator are multiplied by the same constant to convert between the two. **% O_2 in fluegas is not % excess O_2**. Considering these equal is a common error.



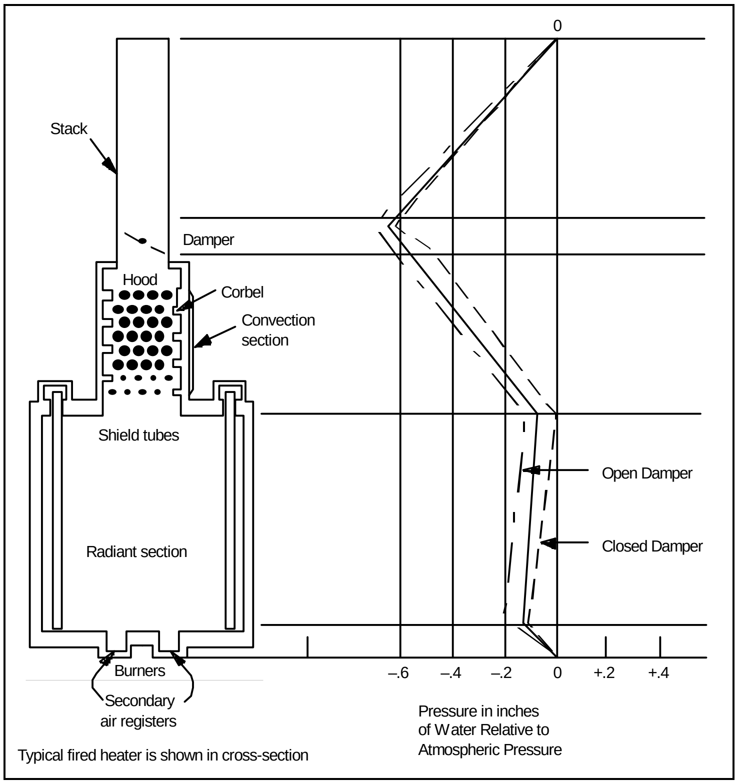
Flue Gas Oxygen Versus Excess Air
Figure 8

Draft

Draft is the negative pressure within the furnace. In a natural draft furnace the draft is caused by the column of hot air within the furnace trying to rise. In designing a natural draft furnace the total available draft can be increased by increasing the stack height. Positive pressure in a natural draft furnace is to be avoided because this usually results in smoking due to inadequate air for combustion. Opening a view port with positive pressure in the furnace might also result in an unsafe condition where an operator could get a face full of fire. Draft is controlled by two principal means: the stack damper; and the burner registers. Figure 9 shows a typical furnace natural draft profile.

In forced draft furnaces natural draft is supplemented by fans. The fans may be on the flue gas (induced draft) or on the air supply (forced draft) or both. Some forced draft furnaces can have positive pressure within the firebox. Windows must be supplied on view ports if the furnace is designed to operate with positive pressure to prevent hot air from burning an operator when trying to use the view ports.

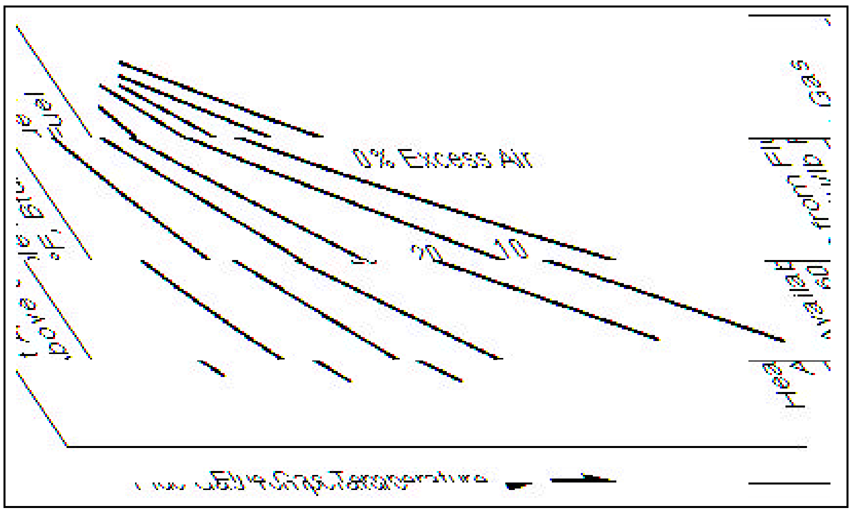
The furnace should operate at a target draft and excess air. A low draft (low pressure drop across the burner) will result in poor mixing of air and fuel at the burner. This will result in long lazy flames which can damage furnace tubes and result in unstable furnace operation.



With permission from the Gas Processors Suppliers Association. Source: Engineering Data Book.
Furnace Natural Draft Profiles
Figure 9

Heat Availability Curves

The combustion heat available to the process in Btu/lb of fuel for various fuels is shown in Maxwell, Pg. 184-188. Heat available to the process is maximized when the stack temperature is equal to the ambient temperature at which air entered the furnace and when there is no excess air. The amount of heat available is reduced whenever the stack temperature is above ambient because heat is being lost in the flue gas. The amount of heat available is reduced by the volume of excess air, since heat is required to heat the excess air from ambient to the stack temperature. Figure 10 shows a typical heat available curve.



Useful in furnace design.
Useful in calculating furnace efficiency.

Combustion Heat Available to Process
Figure 10

Flue Gas Curves

Flue gas curves are used to determine flue gas properties for detailed furnace calculations. The following list covers the curves available in Maxwell.

Title	Page Number
Heat availability curves	184-188
Enthalpy of flue gas components	182-183
Percent CO_2 in flue gas	189
lb flue gas/percent excess air	190
Viscosity of flue gas	191

Thermal conductivity of flue gas	192

Furnace Efficiency

Furnace efficiency is the ratio of the heat absorbed by the process fluid (Q_A) to the total heat fired in the furnace (Q_F) or efficiency = Q_A/Q_F. The heat content of the fuel is expressed two ways, as a high heating value (HHV) and as a low heating value (LHV). The LHV is always used in the furnace efficiency calculation. The heat absorbed by the process fluid (Q_A) can be calculated from the furnace operating conditions or by a heat balance on the process. Once the type of fuel is defined, the furnace flue gas temperature is measured, and the percent excess air at the burner is calculated from the flue gas analysis; heat available (H_A) curves are used to determine how much of the heat fired (Q_F) is available for absorption by the process coil. The required quantity of net fuel (F_N) has to be fired is:

$$F_N = \frac{Q_A \text{ (Btu/hr)}}{H_A \text{ (Btu/lb fuel)}} = \text{lb fuel/hr}$$

Figure 10 is a typical heat available (H_A) curve. The heat available is a function of the stack temperature and the excess air which are the combustion heat losses for the furnace. The net fuel fired required to meet the Q_A duty is further adjusted for heat loss from the furnace firebox (radiant section). This loss typically is about 2%. Therefore, the gross quantity of fuel fired (F_G) to meet Q_A duty is $F_G = (F_N)(1.02)$. The heat fired (Q_F) can be determined from the equation:

$$Q_F = F_G \text{ (lb/hr)} \times \text{LHV (Btu/lb)}$$

Furnace efficiency is:

$$\text{Percent efficiency} = \frac{Q_A (100)}{Q_F}$$

The following backup calculation can be done to check the furnace efficiency calculation. Fuel to a furnace is measured by a flowmeter. The actual rate of fuel should be determined from the fuel meter and a backup of Q_F value calculated from the fuel meter reading. If there is a significant disagreement between Q_F calculated from the efficiency equation and Q_F calculated from the fuel meter, this difference should be reconciled before the calculated furnace efficiency is accepted as a credible value.

The percent excess air at the burner is calculated from the furnace flue gas analysis as was done in Example Problem 1.

Furnace efficiency is governed by two things, flue gas exit temperature (stack temperature) and excess air. The higher the stack temperature, the lower the efficiency. This is because heat that should have gone to process is leaving in the flue gases. Increasing the amount of excess air above the target lowers efficiency. This is because fuel must be burned to raise the excess air from ambient conditions to the stack temperature.

Example Problem 3 shows how an operating furnace efficiency is calculated. It assumes the percentage of excess air has already been calculated (see Example Problem 2 for this method) and a process side heat balance has determined the furnace process heat requirements.

Example Problem 3

Process heat absorbed = Q_A = 353 MBtu/hr (Given)

Stack temperature = 600°F (from stack TI) (Given)

Percent excess air = 5% (from flue gas analysis and calculations of Example Problem 2)

Fuel =	1000 Btu/ft^3 fuel gas	(Given)
	19,700 Btu/lb LHV	(from refinery utilities coordinator) (Given)

From Heat Available Curve: Maxwell, p. 184

H_A = 17,100 Btu/lb fuel at 600°F and 5% excess air

$$\text{Net fuel} = F_N = \frac{Q_A}{H_A} = \frac{353 \times 10^6 \text{ Btu/hr}}{17{,}100 \text{ Btu/lb}} = 20{,}643 \text{ lb/hr}$$

Assume furnace box losses are 2%. (Usually 2 or 3%)

Gross fuel = $F_G = 1.02 \times 20{,}643$ = 21,056 lb/hr

Heat fired = Q_F = 21,056 x 19,700 Btu/lb = 414.8 x 10^6 Btu/hr

$$\text{LHV efficiency} = \frac{\text{heat absorbed}}{\text{heat fired}} = \frac{Q_A}{Q_F} = \frac{353 \times 10^6}{414.8 \times 10^6} \times 100 = 85.1\%$$

Efficiency Shortcut

For a quick approximation of furnace efficiency, the following shortcut formula can be used in conjunction with Figure 8 (percent excess air versus percent O_2 in flue gas curve). This shortcut does not have any adjustment for fuel heating value but does adjust for the ambient temperature.

$$\text{Percent efficiency} = \left[\left(100 - \left(0.0237 + (0.000189)(EA)\right)\right)\left(T_{st} - T_A\right)\right]\left(\frac{100}{100 + Q_L}\right)$$

where:

- EA = Percent excess air.
- T_{ST} = Stack temperature, °F.
- T_A = Ambient air temperature, °F.
- Q_L = Casing heat loss.

This shortcut does not have any adjustment for final heating value but does adjust for the ambient temperature.

For Example problem 3 conditions and assuming that the atmospheric temperature is 80°F, the furnace efficiency calculated from the shortcut formula is as follows:

$$\text{Percent efficiency} = \left[\left(100 - \left(0.0237 + (0.000189)(5)\right)\right)(600 - 80)\right]\left(\frac{100}{100 + 2}\right)$$

$$\text{Percent efficiency} = [100 - (0.0246)(520)](0.9804) = 85.5$$

Combustion Air Preheaters

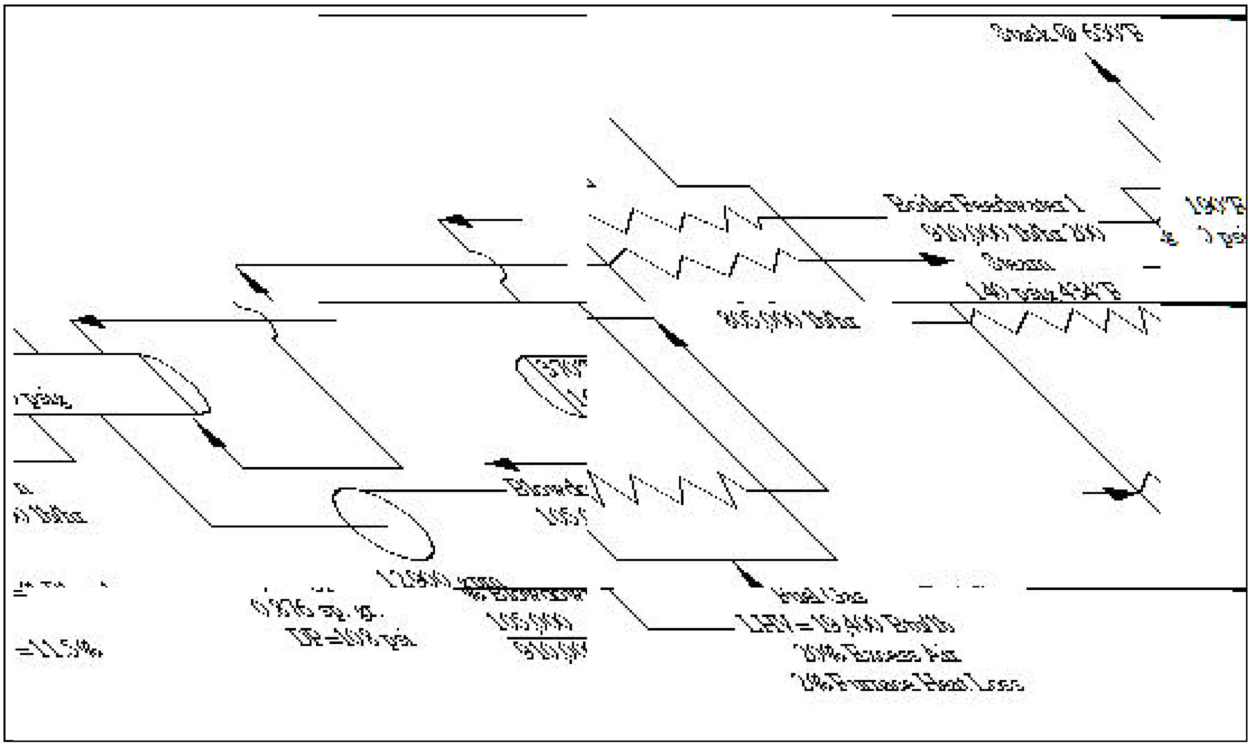
This method of waste heat recovery is one of the two main methods of reducing stack temperature to optimize the thermal efficiency of fired equipment. The other method being waste heat recovery in the convection section.

An air preheater is a heat exchanger that is used to transfer heat from the flue gas leaving a fired heater to the air used for combustion. In this manner, the heater efficiency is increased by reducing the stack temperature below that normally obtained. The capital and operating cost of the air preheater system must be justified by the resulting fuel savings. A 40°F decrease in stack gas temperature usually produces about a 1% increase in furnace efficiency. Lowering the stack temperature to improve efficiency is usually limited by return on investment and the acid dew point in the flue gas.

In addition to the air preheater itself, the air preheater system consists of forced and/or induced draft fans, ducting for flue gas and air, tight shutoff and modulating dampers, and special safety controls and instrumentation.

Example Problem 4

Figure 11 is a schematic of a typical steam boiler system which we have previously solved for the heat absorbed in Module 5. Now we will complete the calculation for furnace efficiency. Blowdown is the system purge required to keep solids that were in the feed water from building up in the system.



Steam Boiler System
Figure 11

Steam Boiler System:

Calculate the fuel required for the boiler in Figure 11. The enthalpy data from a steam table that is needed for entering and exiting streams is shown below:

Stream	Temp., °F	Psia	Enthalpy, Btu/lb H_L	Enthalpy, Btu/lb H_V
Blowdown	370	174.7	343.5	1196.4
Steam	434	154.7	--	1237.6
Feed water	190	--	158.0	--

Heat Balance: Water side/Process

Heat In:	Feedwater	= 910,000 lb/hr x 158	=	143.78 MBtu/hr (M = million)
	Heat Absorbed		=	Q_A
	Total		=	143.78 + Q_A

Heat Out:	Steam	= 805,000 x 1,237.6	=	996.27
	Blowdown	= 105,000 x 343.5	=	36.07
	Total		=	1,032.34 MBtu/hr

Heat In = Heat Out

143.78 + Q_A = 1,032.34

Heat absorbed = Q_A = 1,032.34 - 143.78 = 888.56 MBtu/hr

The furnace efficiency can be calculated as follows:

Process heat required	= 888.56 x 10^6 Btu/hr (Q_A)
Stack temperature	= 650°F (Given)
Percent excess air	= 20 (Given)
Furnace heat loss	= 2% (Given)
Fuel LHV	= 19,400 Btu/lb (Given)
Heat available at 650°F	= 16,450 Btu/lb (Maxwell, p. 185)
Net fuel = $\frac{888.56 \times 10^6}{16,450}$	= 54,016 lb/hr
Gross fuel = 1.02 x 54,016	= 55,096 lb/hr
Heat fired = 19,400 x 55,096	= 1,068.9 x 10^6 Btu/hr
LHV efficiency = $\frac{888.56 \times 10^6}{1,068.9 \times 10^6}$ x 100	= 83.1%

Shortcut Calculation:

$$\text{Percent efficiency} = \left[\left(100 - \left(0.0237 + (0.000189)(EA)\right)\right)\left(T_{st} - T_A\right)\right]\left(\frac{100}{100 + Q_L}\right)$$

$$= \left[\left(100 - \left(0.0237 + (0.000189)\right)\right)(650 - 80)\right]\left[100/(100+2)\right]$$

$$= \left[\left(100 - 0.02748(570)\right)\right]\left[0.9804\right] = 82.7\%$$

What if the ambient temperature was 100°F instead of 80°F?

$$\text{Percent Efficiency} = \left[\left(100 - (0.02748)(650 - 100)\right)\right]\left[0.9804\right] = 83.2\%$$

Increasing the ambient temperature by 20°F improved the efficiency by 0.5% assuming the same stack temperature.

Example Problem 5

Introduction:

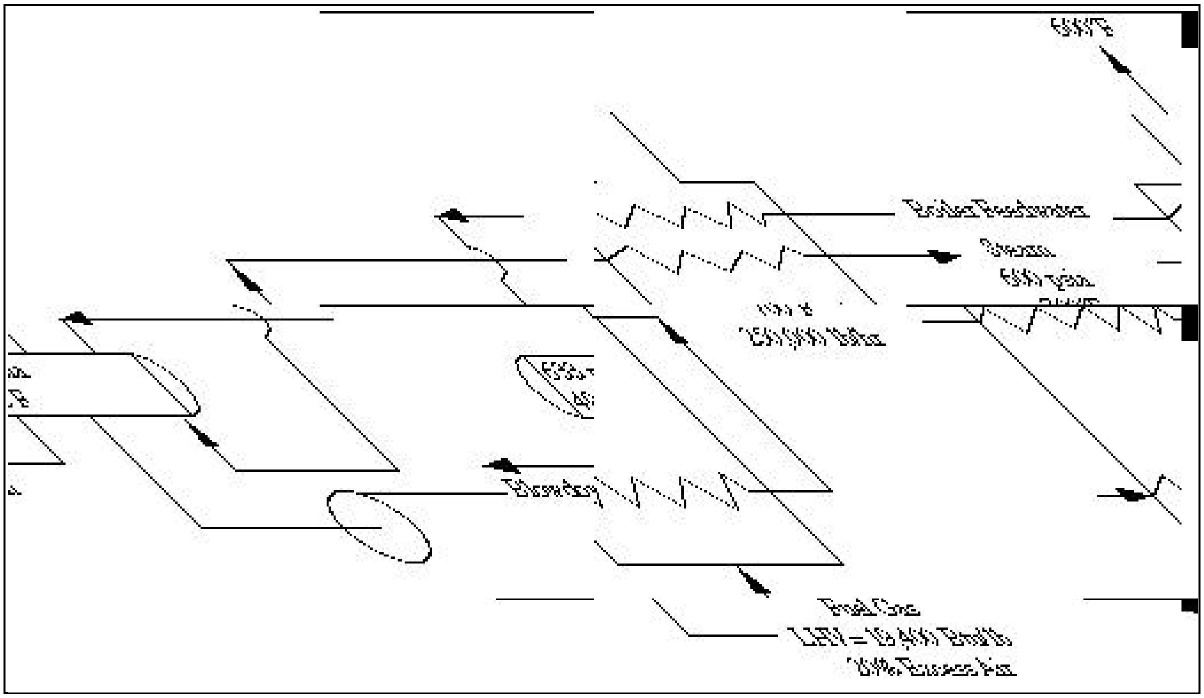
In this example we will perform an energy balance around a boiler system and calculate the fuel it requires. We will also examine methods of efficiency improvement.

Directions:

Calculate the fuel and boiler feedwater required for the boiler system shown in Figure 12. How can the furnace efficiency be improved?

- Use 2% for heat losses.
- Use 10% blowdown.
- For convenience, the required enthalpy data are given below:

Stream	Temp., °F	Psia	H_L	H_V
Feed water	180	--	148.0	--
Steam	700	600	--	1351.8
Blowdown	492	633	478.5	1203.1



Steam Boiler System
Figure 12

Answer:

Material Balance:

Feedrate	=	F
Blowdown	=	0.1 F
Steam product	=	250,000
Material balance, F	=	250,000 + 0.1 F
Feedrate = F	=	$\frac{250,000}{0.9}$ = 277,778 lb/hr
Blowdown = 0.1F	=	27,778 lb/hr

Heat in:	Feed water	=	277,778 x 148	=	41.11 MBtu/hr
	Absorbed Heat	=		=	Q_A
	Total			=	41.11 + Q_A

Heat out:	Blowdown	=	27,778 x 478.5	=	13.29 MBtu/hr
	Steam	=	250,000 x 1351.8	=	337.95
					351.24

Heat in = Heat out $41.11 + Q_A = 351.24$
Heat absorbed $Q_A = 351.24 - 41.11 = 310.13$ MBtu/hr

Heat loss (Given) = 2%

Fuel LHV (Given) = 19,400

Heat available = 16,725 at 600°F Stack and 20% excess air Maxwell, p. 185

Net fuel $= \frac{310.13 \times 10^6}{16,725} = 18,543$

Gross fuel = 1.02 x 18,543 = 18,914
Heat fired = 18,914 x 19,400 = 366.93 MBtu/hr

LHV efficiency $= \frac{310.13 \times 10^6}{366.93 \times 10^6} \times 100 = 84.5\%$

Shortcut efficiency assuming the atmospheric air temperature is 100°F:

$$\text{Efficiency} = [(100 - (0.0237 + (0.000189)(EA)))(T_{ST} - T_A)][100/(100 + Q_L)]$$
$$= [(100 - (0.0237 + (0.000189)(20)))(600 - 100)][100/(100 + 2)]$$
$$= [(100 - 13.74)][0.9804] = 84.5\%$$

To Increase Efficiency:

- Lower stack temperature.
  - Add more surface to convection section and increase boiler feedwater preheat.
  - Add more surface to convection section and preheat another process stream. A 50°F reduction in stack temperature would increase efficiency from 84.5% to 85.9%.

- Reduce blowdown rate.
  - If boiler feedwater quality allows, the blowdown rate can be reduced.
  - Reduction of blowdown from 10% to 2% would not increase the efficiency, but would directly reduce fuel use by decreasing the process heat absorbed.

- Reduce percent excess air.
  - A reduction of excess air from 20% to 10% increases efficiency from 84.5% to 85.4%.

As shown by the table below in Figure 13, the improvements are all of the same order of magnitude. Which one (or all) is used depends on the specific furnace under consideration.

Case	Base	Lower Stack Temp.	Reduce Blowdown	Reduce Excess Air
Percent blowdown	10	10	2	10
Heat absorbed, MBtu/hr	310.13	310.13	302.63	310.13
Stack temperature, °F	600	550	600	600
Excess air, percent	20	20	20	10
Furnace efficiency, percent	84.5	85.91	84.52	85.40
Fuel savings, percent	Base	1.62	2.42	1.04

Furnace Fuel Savings
Figure 13

Calculation for efficiency Improvement:

Case	1 Base	2 Lower Stack Temp.	3 Reduce Blowdown		4 Reduce % Excess Air
Heat in					
277,778 x 148 =	41.11	41.11	255,102 x 148 =	37.76	41.11
Heat out					
27,778 x 478.5 =	13.29		5,102 x 478.5 =	2.44	
250,000 x 1,351.8 =	337.95		250,000 x 1,351.8 =	337.95	
	351.24	351.24		340.39	351.24
Heat absorbed	310.13	310.13		302.63	310.13
Stack	600	550		600	600
Percent excess air	20	20		20	10
Heat loss	2%	2%		2%	2%
Fuel LHV	19,400	19,400		19,400	19,400
Heat avail.*	16,725	17,000		16,725	16,900
Net fuel	18,543	18,243		18,095	18,351
Gross fuel	18,914	18,608		18,457	18,718
Heat fired	366.93	360.99		358.06	363.13
LHV, percent eff.	84.52	85.91		84.52	85.40
Fuel savings	Base	1.62%		2.41%	1.04%

*Maxwell p. 185

FURNACE DESIGN VARIABLES

Metal Temperature

The major design variable in a furnace design is metal temperature and its relationship to yield strength. Yield and creep allowable stress decrease as metal temperature increases as shown in Figure 14. The tube metal temperature is a function of the duty of the furnace, the area of heat transfer surface and the heat transfer coefficient of the fluid inside the tubes. Furnaces are designed with a tube metal temperature low enough to prevent creep of the metal over the service life. Metal temperatures over the design temperature will shorten the tube service life. Creep is the gradual yielding of the metal to stress over time. Exceeding creep limits can result in sagging and/or bulging tubes and may necessitate shutdown for tube replacement.

	Medium Carbon Steel		C-1/2 Mo		1-1/4 Cr-1/2 Mo		2-1/4 Cr-1 Mo		5 Cr-1/2 Mo	
Temp. °F(1)	Elastic Stress	Creep Stress	Elasti c Stress	Creep Stress	Elastic Stress	Creep Stress	Elasti c Stress	Creep Stress	Elasti c Stress	Creep Stress
700	15,800	20,800	15,700		15,250		18,000		16,800	
750	15,500	16,900	15,400		15,000		18,000		16,500	
800	15,000	13,250	15,000		14,600		17,900		15,900	
850	14,250	10,200	14,500		14,250		17,500		15,200	
900	13,500	7,500	14,000	17,000	13,800	17,500	17,100	16,700	14,400	13,250
950	12,600	5,400	13,400	10,250	13,300	10,900	16,500	12,100	13,500	9,600
1,000	11,500	3,700	12,700	5,900	12,800	6,700	15,750	8,700	12,400	7,000
1,050			11,900	3,400	12,100	4,150	14,750	6,400	11,300	5,100
1,100			10,900	2,000	11,400	2,600	13,600	4,600	10,250	3,700
1,150							12,300	3,150	9,200	2,700
1,200							10,700	1,750	8,200	1,950
1,250										

Note: (1) For intermediate temperatures, stresses can be obtained by graphical interpolation.

Source: API Recommended Practice 530, Calculation of Heater Tube Thickness in Petroleum Refineries, Third Edition, September 1988. Reprinted courtesy of the American Petroleum Institute.

Allowable Elastic and Creep Rupture Stress for Typical Heater Tube Materials
(Elastic and Creep Rupture Stress, psi)
Figure 14

The firebox of the radiant section must be large enough so that flames do not impinge on tubes during normal operation. Current designs are about 50,000 Btu/cu. ft. of radiant section volume. Tubes must be at least one tube diameter from the wall to permit proper reradiation from the wall to the tube.

Like tube side heat transfer in exchangers, the tube side heat transfer coefficient is increased as the tube side velocity is increased. As the tube side heat transfer coefficient is increased the tube wall temperature is decreased. When operating near thermal reaction temperatures, it is very important to have high velocities in the tubes to minimize the tube wall temperatures and thereby minimize the thermal degradation of the process fluid. One example of this is a Coker heater. In a Coker heater, the outlet temperature of the heater is controlled above the temperature at which coke formation occurs. Coke deposits are minimized in Coker heaters by adding steam to the process side to increase the process side velocity and by maintaining a high pressure which suppresses vaporization and the coke formation reaction.

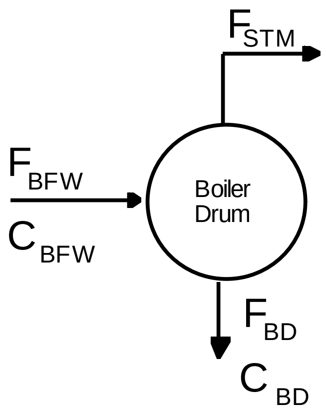
Deposits and Tube Metal Temperature

Deposits insulate the tube wall from the process fluid. The tube wall temperature must increase above design to transfer the design amount of heat because the tube wall is still receiving the same amount of radiation and convection from the furnace side. Deposits can result in a sufficient rise in temperature to cause the tube wall to rupture. Deposits in the tubes are normally observed as hot spots on the tubes. If the temperature of the tube wall increases sufficiently, the stress from pressure in the tube will exceed the yield strength and a rupture can occur. The furnace tube will normally bulge before the rupture occurs but weakening of the metal may be so fast that it may not be observed before a tube failure.

The primary deposit control is proper furnace operation which includes proper burner operation and maintenance. Improper burner operation can result in long flames and possible flame impingement on tubes. Overfiring the furnace above design can also significantly increase metal temperatures in the radiant section. Other controls include blowdown in boilers, pressure control to limit vaporization, proper process side velocities, and additives.

The amount of blowdown required for a boiler will be a function of the water quality (degree of water treating) and the additives used. A boiler system vaporizes feedwater to produce steam. Any impurities in the feedwater are concentrated in the remaining liquid. Boiler systems must purge a portion of the circulating fluid to limit buildup of these impurities. This purge is called blowdown. In some cases, solids in the feed set the blowdown rate, in others the chloride content sets it. This purge requires the feeding of additional water as makeup for the amount discarded. The total boiler feed is, therefore, equal to the steam produced plus the blowdown. Additives are used to prevent solids from dropping out in the boiler tubes and to prevent corrosion.

Boiler blowdown calculations are given below.



$$X = \frac{F_{BD}}{F_{BFW}}(100)$$

$$F_{BFW}\,C_{BFW} = F_{BD}\,C_{BD}$$

$$\frac{C_{BFW}}{C_{BD}} = \frac{F_{BD}}{F_{BFW}} = \frac{X}{100}$$

where:

F_{BFW} = Feedwater flow, lb/hr.
F_{BD} = Blowdown flow, lb/hr.
F_{STM} = Steam flow, lb/hr.
C_{BFW} = Solids concentration in boiler feedwater, ppm.
C_{BD} = Solids concentration of boiler water, ppm.
X = Percent blowdown, as percent of boiler feed water.

Boiler Blowdown Nomenclature
Figure 15

Furnace Side Pressure Drop (Draft)

Calculation of furnace side pressure drops are very complex and will not be covered here. The furnace side pressure drop calculation is complex because the flow is through complex shapes and the temperature of the flue gas (density) is changing rapidly.

Natural draft furnaces are very limited in the pressure drop available. In forced convection furnaces, fans supplement the available natural draft. The fans may be on the air supply (forced draft) or on the flue gas (induced draft) or both. Forced draft furnaces are more expensive than natural draft furnaces but can have the advantage of lower operating costs because they can operate more efficiently. Forced draft makes more energy available for mixing in burners which results in better combustion and the burners can operate at lower levels of excess air without excessive unburned fuel (Carbon Monoxide, CO) and long flames. Forced draft furnaces can have more coils in the convection sections and air preheat because the pressure drop can be accommodated by fans.

Forced draft furnaces are used when firing fuel oil or when there is high pressure drop through the furnace and/or burners. When compared to natural draft furnaces in this service, forced draft systems have the advantages of fewer burners, less burner maintenance, better air/fuel mixing, and closer excess air control because they have a greater pressure drop across the burners

Different natural draft burners have different excess air requirements for proper operation. More stages of combustion (usually more expensive burner) will permit efficient operation at lower levels of excess air.

Process Side Pressure Drop

Calculation of process side pressure drops are very complex and will not be covered here. The process side pressure drop is complex because the temperature and pressure and therefore the amount of vaporization is changing rapidly along the tubes. The principle means of reducing process side pressure drop is by minimizing vaporization, by selecting larger tubes and providing multiple passes. Vaporization can be minimized by increasing system pressure in the heater but this increases the equilibrium temperature which can result in deposits. Heater tube sizes are limited to a fairly low diameter of about 8″ by a combination of temperature, heat transfer, and stress limitations.

Furnace and boiler Operation

Startup

The complexity of fired heaters is increasing. Today, furnace complexity often dictates that a furnace startup advisor be present for major startups. The advisor, together with mechanical, instrument, and burner specialists, review in detail the heater piping and instrumentation. The heater is not ready to be lit for refractory lining dryout until completion of this review and the corrective actions required as a result of this review are completed. The following activities are expected from the startup personnel during the refractory lining dryout and initial furnace operation. If refractory dryout proceeds too fast, water will vaporize inside the refractory which will result in sloughing off of layers of refractory material.

- Review the Operating Manual and revise the fired heater section as necessary (prestartup, oil in, normal operations, shutdown procedures, troubleshooting, and auxiliary equipment instructions).
- Ensure that hydrostatic test water has been removed from the coil to the maximum extent practical.
- Ensure that all fuel lines have been steam blown (not through the burners).
- Check the performance of all the burners during refractory dryout.
- Monitor thermal movements of tubes, tube support systems, and refractory during dryout. Watch for debris on the heater floor.
- Investigate any performance data for the fired heater and attendant equipment, that appears to differ from design specification values. Listed below are some of the more important general observations to be made and problems to look for during an initial startup.
  - Coil and external piping movements.
  - Lining condition as heater reaches operating temperature.
  - Pass flows, pass crossover, and outlet temperature.
  - Tube hot spots and overheated passes.
  - Burner and pilot combustion performance. Watch for problems such as fuel oil dripback, wet atomizing steam, burner orifice plugging, burner tip coking, uneven burner firing rates, leaning flames, flame impingement, burner noise, etc.
  - Draft conditions, particularly at bridgewall.
  - Combustion air pressure.
  - Expansion joint movement.
  - Damper positions.
  - Stack vibration.
  - Fan-induced vibration and noise.
  - Unsafe operating practices.

- Discuss special problems related to the specific fired heater in the operating manual.

When all prestartup activities have been completed (equipment checkout completed, linings dried, etc.), when flow has been established on the process side, and at the appropriate time in the unit oil-in operation, the furnace will be lit and put on-line. The following furnace startup steps are listed for background information and should not be considered complete. In each startup procedure, certain aspects of the procedure are unique to a particular service.

- Check to see if all fuel and pilot systems are active up to unit battery limits.
- Check to see if all drains and vents of the on-fuel/pilot systems are closed.
- Check to see if all instrumentation is working and that automatic shutdown devices are deactivated.
- Commission any fuel oil steam tracing and open blinds at battery limits on fuel/pilot supplies.
- Steam out fuel oil system to bring piping up to temperature.
- Open furnace stack damper fully.
- Start snuffing steam to furnace firebox and shut off snuffing steam when a good flow of steam can be observed from the stack.
- Fully open air dampers on each burner.
- Open valves on pilot gas system to purge inert gases.
- Close (blank) fuel valves. Check for explosibility in furnace. Purge furnace until not explosive.
- Ignite fuel gas pilots, one burner at a time.
- Open valve to bring fuel oil and tracing steam into the burner supply systems.
- Start atomizing steam to the first burner.
- Slowly open the fuel oil valve to the first burner and observe ignition. Adjust oil and air rates to give a stable, nonluminous flame. Set firing at a minimum stable rate consistent with a good flame pattern.
- Repeat for each burner.
- When all burners are lit, check for proper operation of pilot and burner flames.
- Activate furnace instrumentation and raise furnace coil outlet temperature at the rate of about 50°F/hr.

Optimum Excess Air Levels

As part of the discussion on furnace efficiency, some of the furnace operating variables have been discussed, namely:

- Checking the heat absorption Q_A by the heat equation $Q_A = (W)\ (\Delta h)$
- Utilizing the stack flue gas temperature and oxygen content as part of burner operating conditions and furnace efficiency review
- Checking the furnace duty using the fuel rate and LHV.

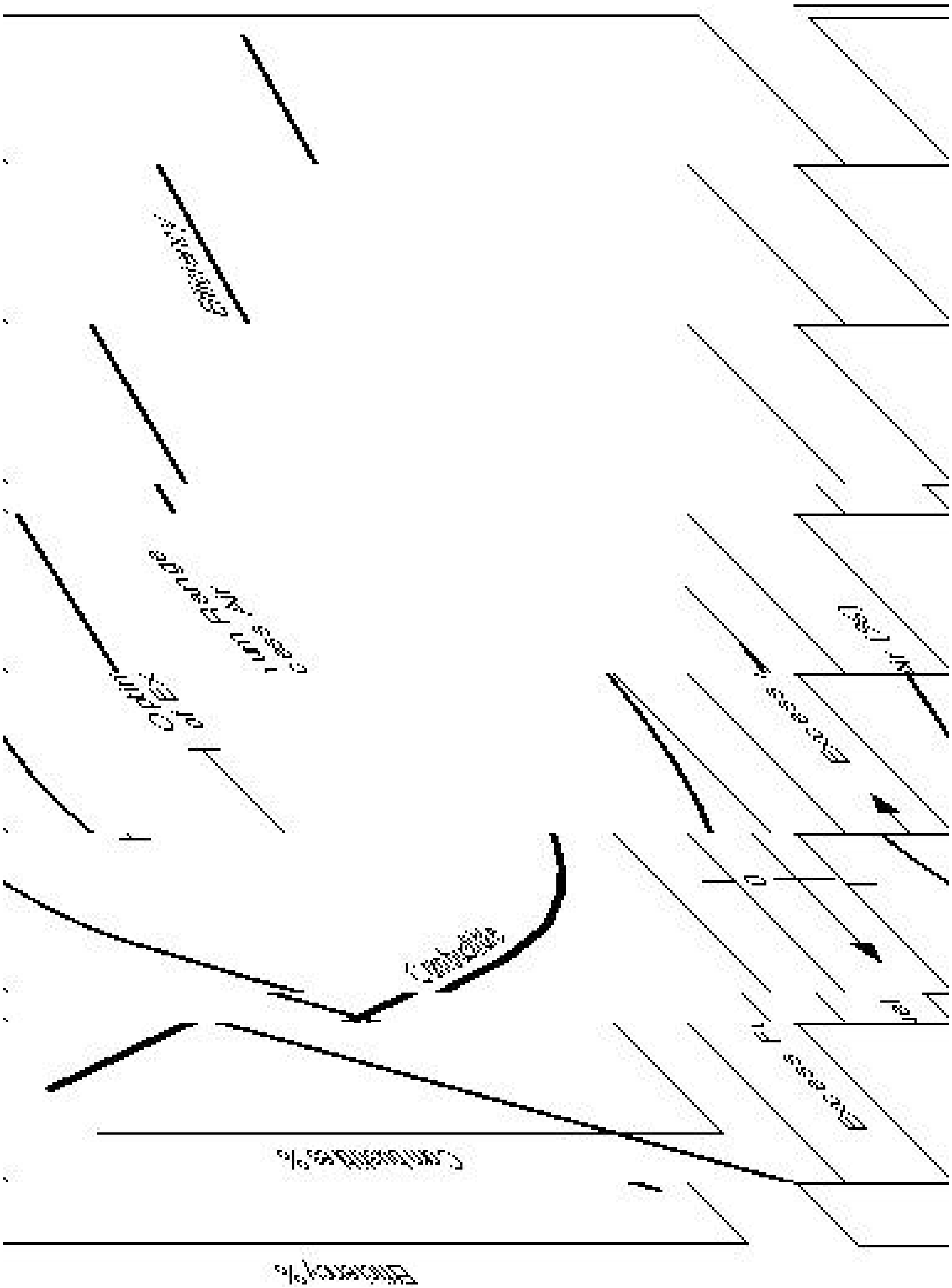
For these variables operating the burner with the correct amount of excess air (determined from O_2 level in flue gas) has the most significant effect on the entire operation of the furnace. Therefore, this discussion will further explore proper excess air levels for furnace burners.

Figures 16 and 17 show the effect of different levels of excess air on the furnace efficiency and level of combustibles in the stack flue gas. An excess air target should be established for each furnace, and the operating level versus the target level should be monitored by the plant operator and engineer or by automatic instrumentation.

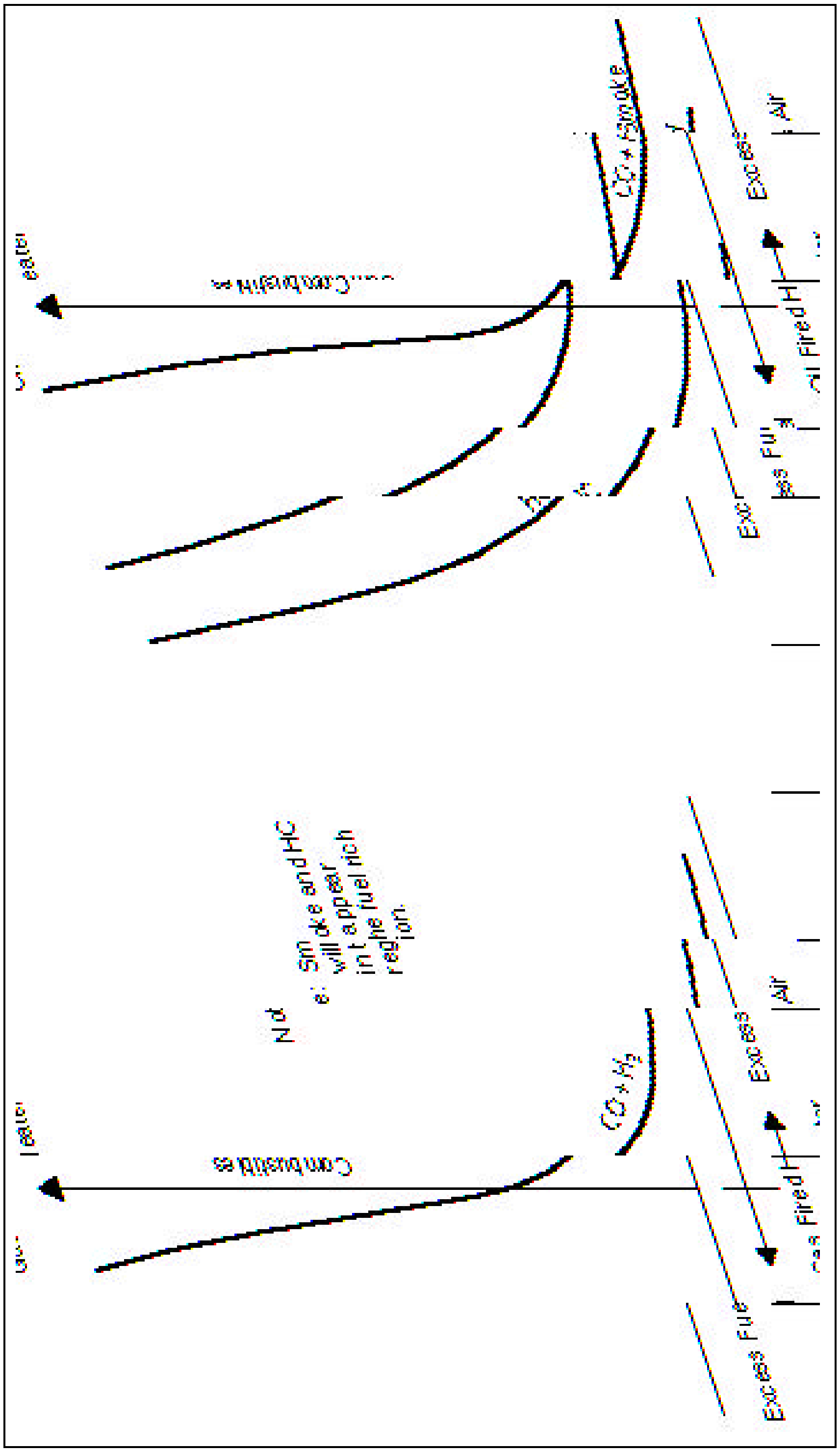
The target excess air level is established by plugging air leaks in the furnace walls and then reducing the air rate to the burner in increments while monitoring the carbon monoxide and smoke level in the stack flue gas. When the carbon monoxide level reaches the 100-200 ppm range, the minimum acceptable excess air level has been reached. The actual monitored target level for excess air will be at or close to this minimum level, as determined by the actual furnace service and associated instrumentation under study. Significant fuel savings can be made by maintaining burner excess air at or close to this minimum level, as determined by the actual furnace service and associated instrumentation under study. Significant fuel savings can be made by monitoring burner excess air. The cost effect of unplugged air leaks is shown in Figure 18.

Operating Guidelines

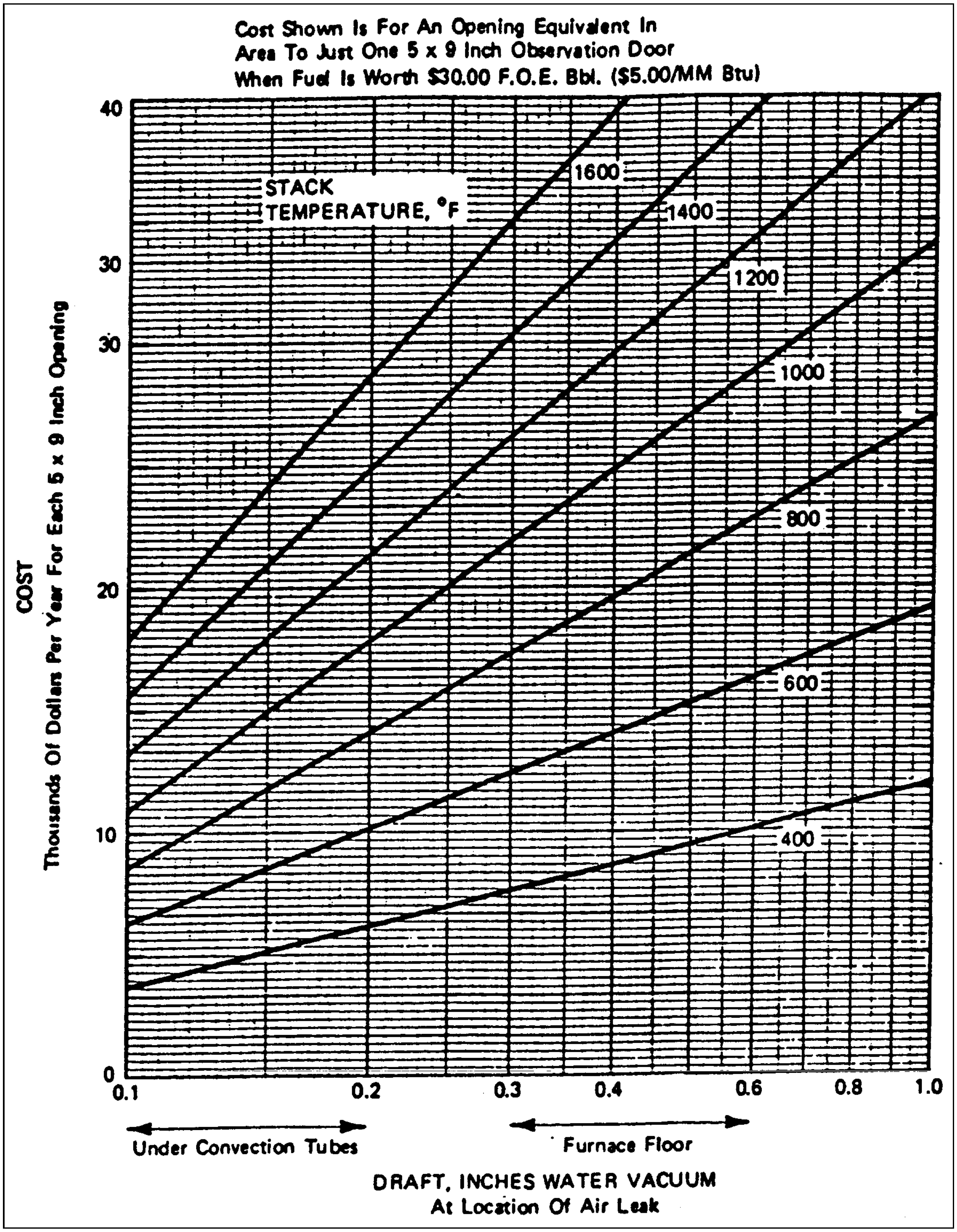
	Low Draft	**High Draft**
Low Excess Air (O_2)	Open Damper	Open Burner Air
High Excess Air (O_2)	Close Burner Air	Close Damper



Optimum Excess Air for a Fired Heater
Figure 16



Typical Combustibles Emission from Fired Heaters
Figure 17



Cost of Furnace Air Leaks
Figure 18

Monitoring Devices and Techniques

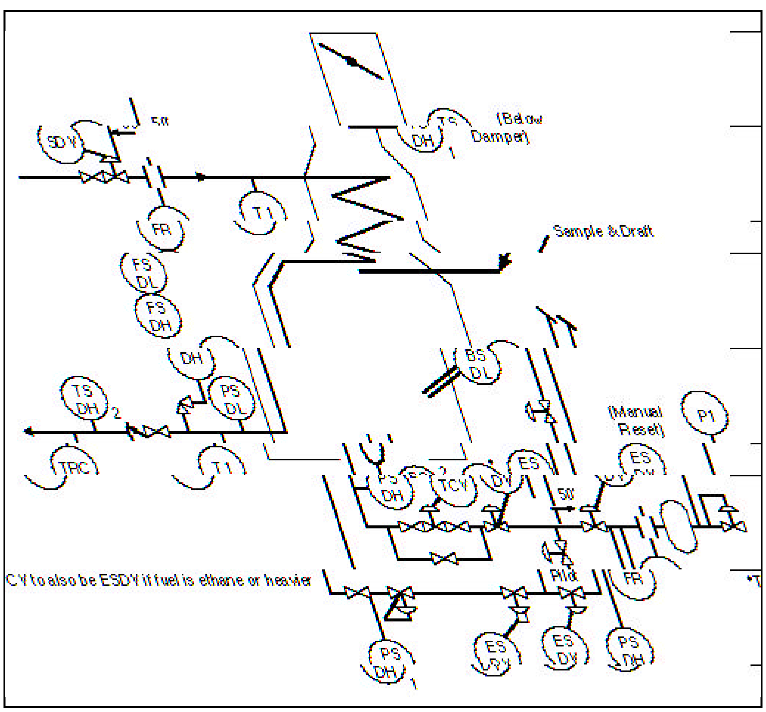
A more extensive discussion on monitoring furnace operations will be presented in a later course. However, for background information, the following are some typical items that can be monitored:

- Process fluid flow pass balancing.
- Tube metal temperatures.
- Bridge wall temperature.
- General firebox conditions.
- Safety equipment.
- Turnaround checklist.

There are computer applications that can be used for furnace monitoring.

Controls/Safety Devices/Burners

Furnace controls and safety devices vary considerably depending on the furnace service and the refinery location. Figure 19 shows an example control system for a direct fired heater. It should not be considered complete, but only representative of the type of instrumentation that should be carefully considered in designing a control system for a furnace service.



With permission from the Gas Processors Suppliers Association. Source: Engineering Data Book.

Example of Direct Fired Reboiler Controls/Safety Devices

Figure 19

The alarms and a description of the shutdown systems shown in Figure 19 are provided in Figure 20.

Schematic Label	Alarm/Shutdown Description	Regeneration Gas Heater	Hot Oil Heater and Direct Fired Reboiler
TSH-1	High stack temperature.	See Note 1.	See Note 1.
TSH-2	High outlet temperature.	See Note 1.	
FSL	Low mass flow through tubes.	See Notes 2 and 4.	See Notes 3 and 4.
BSL	Flame failure detection.	See Note 5.	See Notes 5 and 6.
PSL	Low fuel pressure.		See Note 6.
PSH-1	High fuel pressure.	See Note 7.	See Note 7.
PSH-2	High cabin pressure.	See Note 8.	Not applicable, if natural draft.

Caution: The alarms and shutdowns shown do not necessarily meet any minimum safety requirement, but are representative of the types used for control systems.

Basic Criterion: The failure of any one device will not allow the heater to be damaged.

Notes:
1. A direct immersion jacketed thermocouple is preferred because the response is ten times faster than a grounded thermocouple in a well. A filled bulb system is a poor third choice. The high stack gas temperature shutdown should be set approximately 200°F above normal operation.
2. An orifice plate signal should be backed up by a low pressure shutdown to ensure adequate process stream flow under falling pressure conditions.
3. The measurement should be on the heater inlet to avoid errors from two-phase flow.
4. Differential pressure switches mounted directly across an orifice plate are not satisfactory due to switch does not turn on at the same pressure as it turns off. An analog differential pressure transmitter with a pressure switch on the output is recommended. The analog signal should be brought to the shutdown panel so that the flow level can be readily compared with the shutdown point.
5. The flame scanner should be aimed at the pilot so that a flameout signal will be generated if the pilot is not large enough to ignite the main burner.
6. If the heater design precludes flame scanners, a low fuel gas pressure shutdown should be installed to prevent unintentional flameout. This shutdown should detect gas pressure at the burner.
7. Either burner pressure or fuel control valve diaphragm pr essure may be used. This shutdown should be used whenever large load changes are expected. It prevents the heater from overfiring when the temperature controller drives the fuel wide open to increase heat output with insufficient air.
8. This shutdown should block in all lines to the heater because the probable cause of its activation is tube rupture. Gas is probably burning vigorously outside the heater.

With permission from the Gas Processors Suppliers Association. Source: Engineering Data Book.

Heater Alarm/Shutdown System Description
Figure 20

The parts of the fired heater instrumentation related to safety should be given special attention and regularly inspected as well as tested for functionality. The following items, either observed by the plant engineer or indicated by instrumentation, usually indicate a problem with furnace operations.

- The burner flame is not symmetrical, pulsates or breathes, is unusually long or lazy, lifts off the burner, etc.
- The burner is not aligned and/or the flame is too close to the tubes.
- There is a lack of negative pressure (draft) at the top of the firebox.
- The stack gas is smoky.
- The gas in the firebox appears hazy.
- There are unequal temperatures, differing by more than 10°F, on the process pass outlets indicating unbalanced flows.
- The stack temperature increases steadily with no change in the process heat duty.
- The fuel gas control valve is wide open.
- The fuel gas composition or pressure varies widely.
- The tubes in the heater are not straight.

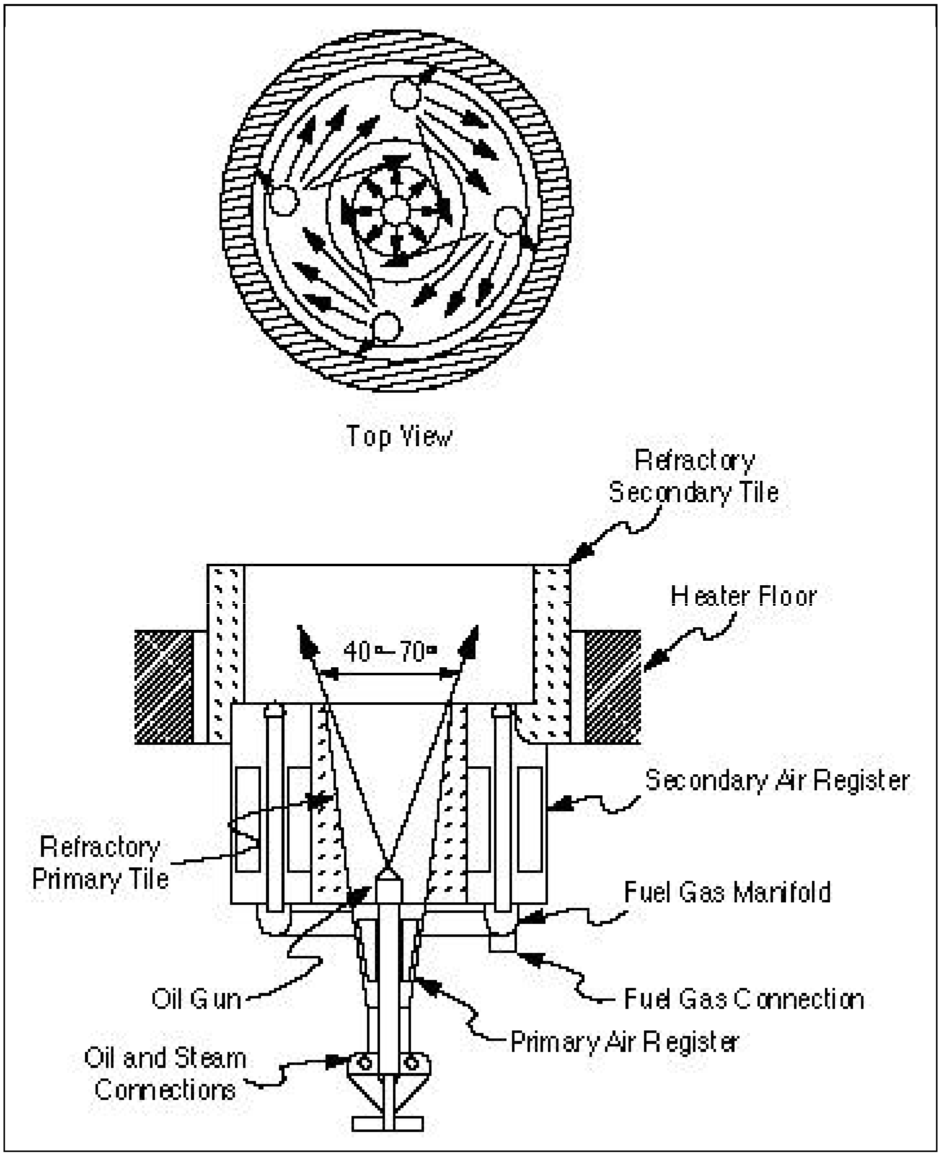
Burner selection is very important because an improper burner will reduce furnace efficiency and service life of tubes. Plant personnel need to have general knowledge of burners so that:

- The proper maintenance will be performed.
- Burner operating problems can be properly diagnosed and corrected.
- The burner operation can be optimized.

Four types of burners are commonly used in direct fired heaters.

- Aspirating Pre-Mix Burners - The passage of fuel gas through a venturi pulls in the combustion air. These burners have short dense flames that are not affected by wind gusts.
- Raw Gas Burners - Some of the air required for combustion is pulled in by a venturi. The rest of the air is admitted through a secondary air register. These burners have larger turndown ratios, require lower gas pressures, and are quieter.
- Low NOx Burners - The addition of a tertiary air register reduces the amount of nitrogen oxides in the flue gas. This type also can be operated with less excess air than aspirating pre-mix or raw gas burners.
- Combination Gas and Oil Burner - An oil burner is added to the gas spider so that fuel oil can also be used. One-tenth pound of steam per pound of fuel is usually required to atomize the oil.

Figure 21 shows a cross-sectional view of a combination gas/oil burner. This module contains limited information on the selection and operation/maintenance of burners. Future courses will explore these subjects in greater depth.



Natural Draft Oil/Gas Burner
Figure 21

Monitoring Tube Metal Temperature

One critical variable to monitor in many furnaces after startup is the tube metal temperatures (temperature of the process coil on the firebox side) in the radiant section. Tube failures account for more than half of the furnace fires and explosions. Excessive tube metal temperatures accelerate tube creep (sagging tubes), hydrogen attack, and external (vanadium attack, oxidation) and internal corrosion of the tubewall. Monitoring tube metal temperatures also helps define the end of the current furnace run, the point at which the furnace is due for a shutdown and decoking.

The measurement of tube wall (tubeskin) temperatures is an attempt to measure metal temperature and thereby the strength of the tube during operations. Increases in metal temperature can be caused by overfiring the furnace, by improper burner operation (long flames cause high tube metal temperatures), by low velocity on the fluid side, and by process side deposits such as coke or salt laydown.

Tube metal temperatures are monitored by thermocouples attached to the tube, or by a pyrometer that measures the radiation emitted by the furnace tubewall. An expert on tubewall temperature instruments should be consulted about the installation of thermocouples or the purchase of a pyrometer. Both measuring devices are sophisticated pieces of equipment that vary in type depending on the service.

Usually, the highest tube metal temperature in a direct fired heater occurs in the radiant section, where the process fluid temperature on the inside of the tube is the highest. The maximum allowable operating tube metal temperature for any one tube material is a function of the tubewall stress level and the severity of the tubewall corrosive atmosphere..

Nomenclature

a_i	Tube inside area, ft^2.
A_o	Heat transfer surface area based on bare tube O.D., ft^2.
a_x	Tube finned area, ft^2.
Cp	Specific heat, Btu/lb °F.
D_e	Equivalent diameter of the bank of finned tubes, $(P/d_r)^2$ (N_f) $(d_o/12)$, ft.
d_i	Inside diameter of tube, in.
d_o	Outside diameter of fins, in.
d_R	Inside diameter of fins, in.
eta_f	Fan efficiency.
eta_d	Driver efficiency.
F_G	Gross fuel fired, lb/hr.
F_N	Net fuel fired, lb/hr.
F_T	LMTD correction factor, from Figure 5.
H_A	Heat available from fuel, Btu/lb fuel.
Q	Total heat load of exchanger, Btu/hr.
Q_A	Furnace process heat absorbed, Btu/hr.
Q_F	Heat fired, Btu/hr.
R	Overall resistance to heat flow, hr ft^2 °F/Btu.
r_{di}	Fouling resistance inside tube, hr ft^2 °F/Btu.
r_{do}	Fouling resistance outside tube, hr ft^2 °F/Btu.
r_m	Resistance to heat flow of tube wall, hr ft^2 °F/Btu.
T_1	Inlet temperature of fluid to be cooled, °F.
T_2	Outlet temperature of fluid to be cooled, °F.
t_1	Inlet temperature of fluid being heated, °F.
t_2	Outlet temperature of fluid being heated, °F.
Δt_e	Effective temperature difference, °F.
Δt_m	Logarithmic mean temperature difference (LMTD), °F.
U_o	Overall heat transfer coefficient (related to bare tube O.D.), Btu/hr ft^2 °F.
W_t	Process fluid rate, lb/hr.

References

1. Chemical Engineer's Handbook, 6th Edition, R. H. Perry and D. Green (Physical properties, general information, calc equations).

2. Data Book on Hydrocarbons, J. B. Maxwell (Hydrocarbon physical properties).

3. Engineering Data Book, Gas Processors Suppliers Association, 10th Edition, 1987.

4. Process Heat Transfer, Kern, 1950.

5. Furnace Operations, Robert Reed, 1981

6. API RP J30 Calculation of Heater Tube Thickness in Petroleum Refining

WORK AID

WORK AID 1: PROCEDURES FOR CALCULATING FURNACE EFFICIENCY

This work aid will assist the Participant in Exercise 1: Calculate Furnace Efficiency.

To determine a furnace thermal efficiency, follow the steps listed below:

Step 1: Calculate oxygen to furnace, using the formula:

$$O_2 \text{ to furnace/100 moles flue gas} = \frac{\left(\dfrac{\text{moles } N_2}{\text{100 moles flue gas}}\right)\left(\dfrac{\text{moles } O_2}{\text{100 moles of air}}\right)}{\left(\dfrac{\text{moles } N_2}{\text{100 moles of air}}\right)}$$

$$= \frac{\left(\dfrac{\text{moles } N_2}{\text{100 moles flue gas}}\right)(21)}{79}$$

Step 2: Calculate percent excess oxygen (air), using the formula:

$$\text{Percent excess} O_2 = \frac{\left(\dfrac{\text{moles } O_2 \text{ from furnace}}{\text{100 moles flue gas}}\right)(100)}{\left(\dfrac{\text{moles } O_2 \text{ to furnace}}{\text{100 moles flue gas}}\right) - \left(\dfrac{\text{moles } O_2 \text{ from furnace}}{\text{100 moles flue gas}}\right)}$$

Percent excess O_2 = percent excess air.

Note: If there is CO in the flue gas, refer to Example Problem 1 for adjustment of excess oxygen.

Step 3: Determine heat absorbed, Q_A:

$Q_A = (W)\ (\Delta h)$

$Q_A = (W)\ (C_p)\ (\Delta t)$ if no vaporization

Step 4: Determine heat available (H_A) per lb of fuel from Maxwell, p. 185.

Step 5: Calculate net fuel fired, F_N:

$$F_N = \frac{Q_A}{H_A}$$

Step 6: Calculate gross fuel fired, F_G. Assume furnace heat losses are 2 1/2%.

$$F_G = 1.025\ (F_N)$$

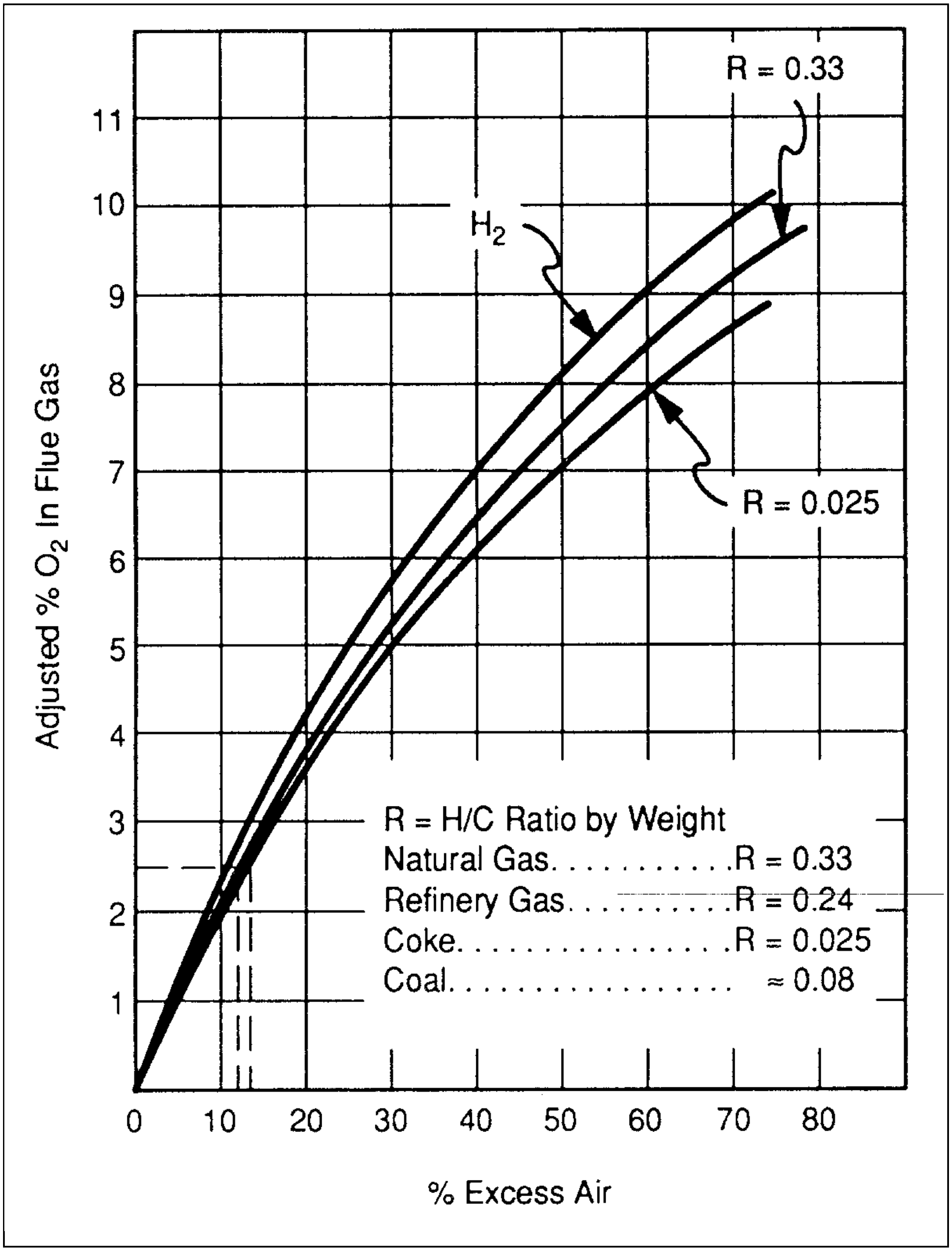
Step 7: Calculate heat fired, Q_F, Btu/hr.

$$Q_F = (F_G)\ (\text{LHV fuel})$$

Step 8: Calculate furnace efficiency:

$$\%\ \text{efficiency} = \frac{Q_A\ (100)}{Q_F}$$

WORK AID 2: FLUE GAS OXYGEN VERSUS EXCESS AIR



Flue Gas Oxygen Versus Excess Air
Figure 8

GLOSSARY

acid dew point	The temperature at which an acidic component in the flue gas condenses.
bubble point curve	Denotes the family of pressure/temperature points at which the fluid starts to vaporize.
burner registers	The openings, equipped with a regulating device, in the burner to feed air to the burner.
contamination	The quality of a substance is made unacceptable by a contaminant. This reduction in quality is called contamination.
corbeled wall	An irregular wall in the convection section of a furnace. The irregularities in the wall match the staggered tubes in the convection section to prevent flue gas from bypassing around the tubes.
dew point curve	Denotes the family of pressure/temperature points at which the fluid starts to condense.
extended surface	The metal surface area for a tube including the tube fin area.
flame impingement	The burner flames touch the tubes.
furnace bridgewall	The top of the radiant section where the hot gases enter the convection section.
lining dryout	Castable furnace refractory linings have been mixed with water at installation; this excess water is slowly boiled out of the lining during dryout.
nonluminous flame	An improperly adjusted burner flame is yellow and luminous (it gives off light). A properly adjusted flame is a light blue and gives off very little light.
serrated fin	A fin surface with many cuts, breaks.

slug flow	A very uneven flow with alternate slugs (sections) of liquid followed by vapor.
snuffing steam	Steam injected into furnace firebox to extinguish a fire or purge the firebox to prevent an explosion when burners are lit.
stack gas combustibles	Material in the stack gas that was not fully burnt (combusted) in the furnace.
toxicity	The adverse effect of a substance on human health.