

Simplify your thermal efficiency calculation

Standard charts and a spreadsheet help

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Most process engineers recognize the value of furnace efficiency calculations, yet many are intimidated by the idea of performing them. The thermal efficiency calculation is important for evaluating its furnace performance.

Engineers can no longer hope to be successful in evaluating furnace operation without a grasp of fundamentals and their applications to solving furnace problems. Focusing on the fundamentals of furnace calculations provides a framework for engineers to gain information and understand operations. For anyone who routinely wants to perform efficiency calculations, a spreadsheet program is necessary. This article can help develop it.

A previous article shows how to calculate the thermal efficiency using flue gas analysis.¹ The method described in this article considers fuel gas analysis and stack temperature to calculate the thermal efficiency. The procedure uses standard charts for excess air and enthalpy of flue gas components to simplify the calculations. The difference between the simplified calculation and the correct one is smaller, and its impact on the final calculation is negligible.

The method described is intended for fired heaters burning only gaseous fuels only. By understanding the procedure described, engineers will be able to calculate the following:

- Lower heating value (*LHV*) or fuel heat of combustion
- Combustion air and flue gas flowrates
- Flue gas composition (both wet and dry basis)
- Furnace thermal efficiency.

Efficiency. The net thermal efficiency is equal to the total heat absorbed divided by the total heat input. The heat absorbed is equal to the total heat input minus the total heat losses from the system.

The net thermal efficiency for the arrangements shown in Fig. 1 can be determined by the following equation:

$$\text{Efficiency} = \frac{\text{Total heat input} - \text{Stack heat losses} - \text{Radiation heat loss}}{\text{Total heat input}} \times 100$$

Therefore,

$$e = \frac{(LHV + Ha + Hf) - Q_s - Q_r}{(LHV + Ha + Hf)} \times 100 \quad (1)$$

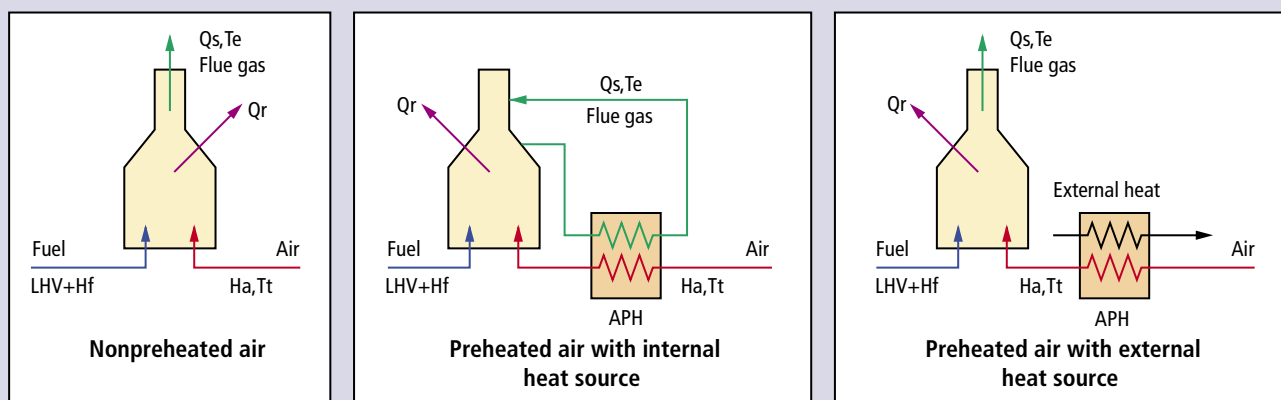


FIG. 1 Eq. 1 can be used to determine the net thermal efficiency for these arrangements.

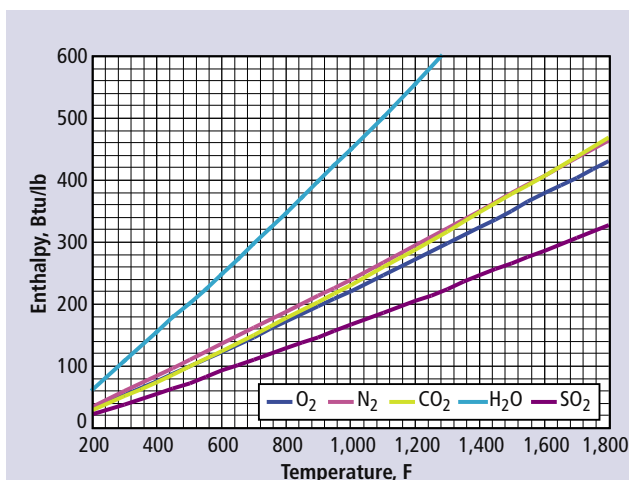


FIG. 2 Enthalpies of O₂, N₂, CO₂, H₂O and SO₂.

where: e = Net thermal efficiency, %

LHV = Heat input or lower heating value of the fuel, Btu/lb of fuel

Ha = Heat input in the form of sensible heat of air, Btu/lb of fuel

Hf = Heat input in the form of sensible heat of fuel, Btu/lb of fuel

Q_s = Calculated stack heat losses, Btu/lb of fuel

Q_r = Assumed radiation heat loss, Btu/lb of fuel

Heat input. Total heat input is the sum of the fuel LHV and sensible heat of air and fuel. LHV /lb of fuel is calculated using fuel gas analysis and the net heating value of fuel components. The heat of combustion is calculated by multiplying the weight fraction of fuel components by its net heating value. The total heat of combustion is then divided by the total fuel weight to obtain the LHV .

Ha and Hf are estimated using the following equations:

$$Ha = \frac{\text{lb of air}}{\text{lb of fuel}} \times C_{p_{air}} \times (T_t - T_d)$$

$$Hf = C_{p_{fuel}} \times (T_f - T_d)$$

where: $C_{p_{air}}$ = Specific heat of air

$C_{p_{fuel}}$ = Specific heat of fuel

T_t = Combustion air temperature

T_f = Fuel temperature

T_d = datum temperature (60°F).

Heat losses. Total heat losses are the sum of stack and radiation heat losses. The stack heat losses, Q_s /lb of fuel, are determined from a summation of the enthalpy of the flue gas components at the stack temperature, T_s . Fig. 2 is used to estimate the enthalpy of flue gas components/lb of fuel.

One of the key steps in estimating the heat losses is to calculate the flue gas components produced/lb of fuel:

$$\text{Flue gas} = \text{Fuel} + \text{Combustion air}$$

So, the first step in calculating the heat losses is to determine how much combustion air/lb of fuel is required.

Estimating the theoretical or stoichiometric moles of oxygen required to complete the combustion will help to calculate the combustion air. The theoretical moles of oxygen required for combustion are calculated using the combustion reactions shown in Table 1. For example, one mole of H₂ requires 0.5 moles of oxygen. So, if H₂ is one of the fuel components, the volume fraction of H₂ is multiplied by 0.5 to calculate the moles of oxygen required by H₂. The moles of oxygen required by other fuel components are calculated similarly.

Once the total theoretical moles of oxygen are calculated, it's very easy to calculate the moles of combustion air.

Air is 21% oxygen by volume. So,

$$\text{Theoretical moles of combustion air} = \text{Moles of oxygen} \times 100/21$$

The total theoretical moles of air are then corrected for excess air to get the actual moles of combustion air required.

Remember,

$$\text{Actual moles of air} = \text{Theoretical moles of air} + \text{Excess air.}$$

Based on percent oxygen content in the flue gas (generally, an oxygen analyzer reading is used here), excess air can be estimated using Fig. 3. This chart can be used for natural and refinery fuel gases.

After correcting the theoretical moles of combustion air with excess air, the combustion air/lb of fuel is calculated by multiplying the moles of combustion air by 29 (MW of air) and then dividing by the total fuel weight.

Once the quantity of combustion air is determined, the next step is to calculate flue gas components produced/lb of fuel. The flue gas components are mainly CO₂, H₂O, SO₂, O₂ and N₂.

Hence,

$$\text{Moles of flue gas components} = \text{CO}_2 (\text{Moles of CO}_2 \text{ formed during combustion} + \text{Moles of CO}_2 \text{ available as a fuel}) + \text{H}_2\text{O} (\text{Moles of H}_2\text{O formed during combustion})$$

TABLE 1. Combustion reactions

Reaction	Moles of O ₂ required	Moles of CO ₂ formed	Moles of SO ₂ formed	Moles of H ₂ O formed
H ₂ + 0.5O ₂ → H ₂ O	0.5	0	1	0
CO + 0.5O ₂ → CO ₂	0.5	1	0	0
CH ₄ + 2O ₂ → CO ₂ + 2H ₂ O	2	1	2	0
C ₂ H ₆ + 3.5O ₂ → 2CO ₂ + 3H ₂ O	3.5	2	3	0
C ₂ H ₄ + 3O ₂ → 2CO ₂ + 2H ₂ O	3	2	2	0
C ₃ H ₈ + 5O ₂ → 3CO ₂ + 4H ₂ O	5	3	4	0
C ₃ H ₆ + 4.5O ₂ → 3CO ₂ + 3H ₂ O	4.5	3	3	0
C ₄ H ₁₀ + 6.5O ₂ → 4CO ₂ + 5H ₂ O	6.5	4	5	0
C ₄ H ₈ + 6O ₂ → 4CO ₂ + 4H ₂ O	6	4	4	0
C ₅ H ₁₂ + 8O ₂ → 5CO ₂ + 6H ₂ O	8	5	6	0
C ₆ H ₁₄ + 9.5 O ₂ → 6CO ₂ + 7H ₂ O	9.5	6	7	0
S + O ₂ → SO ₂	1	0	0	1
H ₂ S + 1.5O ₂ → SO ₂ + H ₂ O	1.5	0	1	1

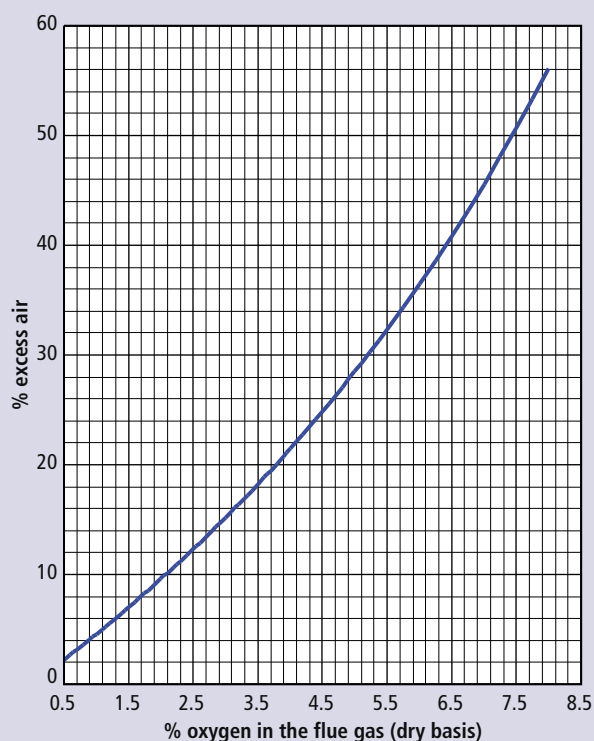


FIG. 3 Relationship between oxygen content in the flue gas and excess air.

tion + Moles of H_2O available as a fuel) + SO_2 (Moles of SO_2 formed during combustion + Moles of SO_2 available as a fuel) + O_2 (Moles of oxygen supplied - Moles of oxygen used during the combustion) + N_2 (Moles of N_2 available from air + Moles of N_2 available as a fuel)

The moles of CO_2 , H_2O and SO_2 formed during combustion are calculated using the reactions shown in Table 1. The method will be the same, which is used for calculating oxygen requirements.

Once the total moles of flue gas components are determined, the flue gas components/lb of fuel is calculated by multiplying the moles of flue gas components by its molecular weight and then dividing by the total fuel weight.

The flue components produced/lb of fuel calculation requires correction for the moisture coming with the air and fuel, but this step can be eliminated since its impact on the final calculation is negligible.

The radiation heat loss, Q_r /lb of fuel is determined by multiplying the LHV by radiation loss expressed as a percentage. Generally, this loss is between 2% and 4%.

Sample problem:

Heater name	Plant 15-1F-1 (hydrogen heater)
Location	Syn crude Canada Ltd., Fort McMurray, Canada
Flue gas exit temperature, °F	348

Ambient air temperature	50
Combustion air temperature, °F	68
Fuel gas temperature, °F	77
Oxygen in the flue gas, vol. %	3.2 (dry basis)
Assumed radiation losses, %	2.5
Fuel composition, mol./vol. %	Methane: 36.51, hydrogen: 22.80, ethane: 13.49, ethylene: 6.28, propane: 8.20, propylene: 5.95, butane: 1.92, butylene: 2.06, pentane: 0.44, nitrogen: 1.43, carbon monoxide: 0.74, carbon dioxide: 0.17, hydrogen sulfide: 0.0048

Solution: Basis: 100 moles/hr of fuel is fired in the furnace.

Follow this step-by-step procedure to determine the thermal efficiency and other parameters.

LHV of fuel/lb of fuel. The fuel LHV is calculated using a combustion work sheet (Table 2). Instructions for developing the combustion work sheet are:

Insert fuel composition in column A and its quantity as a volume fraction in column B. If the composition is expressed as a weight percent, then insert in column D. Insert mol. wt. of fuel components in column C. Multiply column B by column C to get the total weight in column D. Total column D on the total line to obtain total fuel flow.

Therefore,

$$\text{Total fuel flow} = 2,147.89 \text{ lb/hr}$$

Now, insert net heating value (Btu/lb) of all the components in column E (from process handbook). Multiply column D by column E to get the heating value of all the components in column F. Total column F on the total line. Divide the column F total by the column D total to obtain the fuel LHV .

Therefore,

$$LHV = 20,483 \text{ Btu/lb of fuel}$$

Combustion air/lb of fuel. From the combustion reactions shown in Table 1, each mole of CH_4 requires 2 moles of O_2 , etc.

In your combustion work sheet, multiply 36.51 (CH_4 mol fraction in column B) by 2 (moles of oxygen) to calculate theoretical or stoichiometric oxygen required for CH_4 in column G and so on. Then total column G on the total line to obtain the quantity of total oxygen required.

Therefore,

$$\text{Total theoretical (stoichiometric) oxygen required} = 246.99 \text{ moles/hr}$$

Oxygen in the flue gas is reported as 3.2% vol. (dry). An estimated excess air corresponding to the 3.2% oxygen in the flue gas is 16.4%. (See Fig. 3 for relationship between oxygen content in the flue gas and excess air.)

Therefore,

$$\begin{aligned} \text{Actual oxygen required} &= 246.99 \times 1.164 \\ &= 287.50 \text{ moles/hr} \end{aligned}$$

TABLE 2. Combustion work sheet

A	B	C	D (B X C)	E	F (D X E)	G	H	I	J
Fuel Component	Vol. fraction, (moles/hr)	Mol. wt.	Total weight (lb/hr)	Net heating value, Btu/lb	Heating value, Btu/hr	Theoretical or Stoichiometric oxygen required, moles/hr	CO ₂ formed during combustion, moles/hr	H ₂ O formed during combustion, moles/hr	SO ₂ formed during combustion, moles/hr
Methane (CH ₄)	36.51	16.00	584.16	21,500	12559440	73.02	36.51	73.02	0.00
Hydrogen (H ₂)	22.80	2.00	45.60	51,600	2352960	11.40	0.00	22.80	0.00
Ethane (C ₂ H ₆)	13.49	30.00	404.70	20,420	8263974	47.22	26.98	40.47	0.00
Ethylene (C ₂ H ₄)	6.28	28.00	175.84	20,290	3567794	18.84	12.56	12.56	0.00
Propane (C ₃ H ₈)	8.20	44.00	360.80	19,930	7190744	41.00	24.60	32.80	0.00
Propylene (C ₃ H ₆)	5.95	42	249.90	19,690	4920531	26.78	17.85	17.85	0.00
Butane (C ₄ H ₁₀)	1.92	58	111.36	19,670	2190451	12.48	7.68	9.60	0.00
Butylene (C ₄ H ₈)	2.06	56	115.36	19,420	2240291	12.36	8.24	8.24	0.00
Pentane (C ₅ H ₁₂)	0.44	72	31.68	19,500	617760	3.52	2.20	2.64	0.00
Nitrogen (N ₂)	1.43	28	40.04	0	0	0.00	0.00	0.00	0.00
Carbon monoxide (CO)	0.74	28	20.80	4,345	90393	0.37	0.74	0.00	0.00
Carbon dioxide (CO ₂)	0.17	44	7.48	0	0	0.00	0.00	0.00	0.00
Hydrogen sulfide (H ₂ S)	0.00480	34	0.16	6,550	1069	0.01	0.00	0.0048	0.0048
Total	100.00		2,147.89		43,995,407	246.99	137.36	219.98	0.00480
Total/lb of fuel					20,483				

Air is 21% oxygen by volume,

Therefore,

$$\begin{aligned}
 \text{Actual air required} &= 287.50 \times (100/21) \\
 &= 1,369.02 \text{ moles/hr} \\
 &= 1,369.02 \times 29 \text{ (mol. wt. of air)} \\
 &= 39,702 \text{ lb/hr}
 \end{aligned}$$

$$\begin{aligned}
 \text{Actual air/lb of fuel} &= 39,702/2,147.89 \\
 &= 18.48 \text{ lb/lb of fuel}
 \end{aligned}$$

Flue gas/lb of fuel.

$$\begin{aligned}
 \text{Flue gas} &= \text{Fuel} + \text{Combustion air} \\
 &= 2,147.89 \text{ lb/hr} + 39,702 \text{ lb/hr} \\
 &= 41,850 \text{ lb/hr}
 \end{aligned}$$

$$\begin{aligned}
 \text{Flue gas/lb of fuel} &= 41,850/2,147.89 \\
 &= 19.48 \text{ lb/lb of fuel}
 \end{aligned}$$

Flue gas composition. From the combustion reactions shown in Table 1, each mole of CH₄ produces 2 moles of CO₂, 1 mole of H₂O and, etc.

In your combustion work sheet, multiply 36.51 (mole fraction of CH₄) by 2 (moles of CO₂) to calculate the moles of CO₂ formed in column H, etc. Repeat this step for H₂O and SO₂ and calculate the moles of H₂O and SO₂ formed in columns I and J, respectively. Total columns H, J and I.

Therefore,

$$\begin{aligned}
 \text{Total CO}_2 \text{ formed} &= 137.36 \text{ moles/hr} \\
 \text{Total H}_2\text{O formed} &= 219.98 \text{ moles/hr} \\
 \text{Total SO}_2 \text{ formed} &= 0.0048 \text{ moles/hr}
 \end{aligned}$$

TABLE 3. Flue Gas Heat Loss Work Sheet

A	B	C	D (B X C)	E	F	G (E X F)
Flue Gas component	Moles/hr	Mol. wt.	Weight, lb/hr	Total weight/lb of fuel	Enthalpy at 348°F	Heat content, Btu/lb of fuel
CO ₂	137.53	44	6051.45	2.82	62	174.68
H ₂ O	219.98	18	3959.73	1.84	128	235.97
SO ₂	0.0048	64	0.31	0.0001	44	0.0063
O ₂	40.51	32	1296.20	0.60	65	39.23
N ₂	1082.96	28	30322.83	14.12	73	1030.58
Total	1480.98					1480.46

Flue Gas.

$$\begin{aligned}
 \text{CO}_2 \text{ in the flue gas} &= \text{CO}_2 \text{ formed during combustion} + \text{CO}_2 \text{ reported as a fuel} \\
 &= 137.36 \text{ moles/hr} + 0.17 \text{ moles/hr} \\
 &= 137.53 \text{ moles/hr}
 \end{aligned}$$

$$\begin{aligned}
 \text{H}_2\text{O in the flue gas} &= \text{H}_2\text{O formed during combustion} + \text{H}_2\text{O reported as a fuel} \\
 &= 219.98 \text{ moles/hr} + 0 \\
 &= 219.98 \text{ moles/hr}
 \end{aligned}$$

$$\begin{aligned}
 \text{SO}_2 \text{ in the flue gas} &= \text{SO}_2 \text{ formed during combustion} + \text{SO}_2 \text{ reported as a fuel} \\
 &= 0.0048 \text{ moles/hr} + 0 \\
 &= 0.0048 \text{ moles/hr}
 \end{aligned}$$

$$\begin{aligned}
 \text{O}_2 \text{ in the flue gas} &= \text{Actual O}_2 \text{ supplied} - \text{Actual O}_2 \text{ used during combustion} \\
 &= 287.50 - 246.99
 \end{aligned}$$

$$= 40.51 \text{ moles/hr}$$

$$\begin{aligned} N_2 \text{ in the flue gas} &= N_2 \text{ from air (moles of air - moles of oxygen)} + N_2 \text{ reported as a fuel} \\ &= (1,369.02 - 287.50) + 1.43 \\ &= 1,082.95 \text{ Moles/hr} \end{aligned}$$

Therefore,

Components	moles/hr	Wet basis vol%/mol%	Dry basis vol%/mol%
CO ₂	137.53	9.29	10.91
H ₂ O	219.98	14.85	0.00
SO ₂	0.0048	0.00032	0.00038
O ₂	40.51	2.74	3.21
N ₂	1,082.95	73.12	85.88
Total	1,480.98	100	100.00

Stack Heat Losses Q_s /lb of fuel. The stack heat losses are determined from a summation of the heat content of the flue gas components at the exit flue gas temperature. The stack or flue gas exit temperature is 348°F. The heat content of flue gas is calculated using the stack heat loss work sheet (Table 3). Instructions for developing the stack heat loss work sheet are:

Insert flue gas components in column A and its quantity in column B. Insert mol. wt. of flue gas components in column C. Multiply column B by column C to obtain the total weight in column D. Now, divide column D by total fuel weight (2,147.89 lb/hr) to obtain flue gas components/lb of fuel in column E. In column F, insert the enthalpy values for flue gas components. Refer to Fig. 2 to get the enthalpy of flue gas components at 348°F. Now, multiply column E by column F to calculate the heat content of flue gas in column G. Total column G to obtain the Q_s at 348°F.

$$\text{Therefore, } Q_s = 1,480.46 \text{ Btu/lb of fuel}$$

Radiation heat loss Q_r /lb of fuel. The radiation heat loss is determined by multiplying heat input fuel LHV by the radiation loss expressed as a percentage. The radiation heat loss is 2.5%.

$$\begin{aligned} \text{Therefore, } Q_r &= 20,483 \times 0.025 \\ &= 512 \text{ Btu/lb of fuel} \end{aligned}$$

Sensible heat correction for combustion air, H_a /lb of fuel.

$$\begin{aligned} H_a &= \text{lb of air/lb of fuel} \times C_{p_{\text{air}}} \times (T_t - T_d) \\ &= 18.48 \times 0.24 \times (68 - 60) \\ &= 35.48 \text{ Btu/lb of fuel} \end{aligned}$$

Sensible heat correction for fuel H_f /lb of fuel.

$$\begin{aligned} H_f &= C_{p_{\text{fuel}}} \times (T_f - T_d) \\ &= 0.53 \times (77 - 60) \\ &= 9.01 \text{ Btu/lb of fuel} \end{aligned}$$

Net thermal efficiency. The net thermal efficiency can then be calculated as follows (Eq. 1):

$$\begin{aligned} \text{Efficiency} &= \frac{(20,483 + 35.48 + 9.01) - (1,480.46 - 512)}{(20,483 + 35.48 + 9.01)} \times 100 \\ &= 90.29\% \end{aligned} \quad (1)$$



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