HEAT TRANSFER   **BONUS**REPORT

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:

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

Therefore,

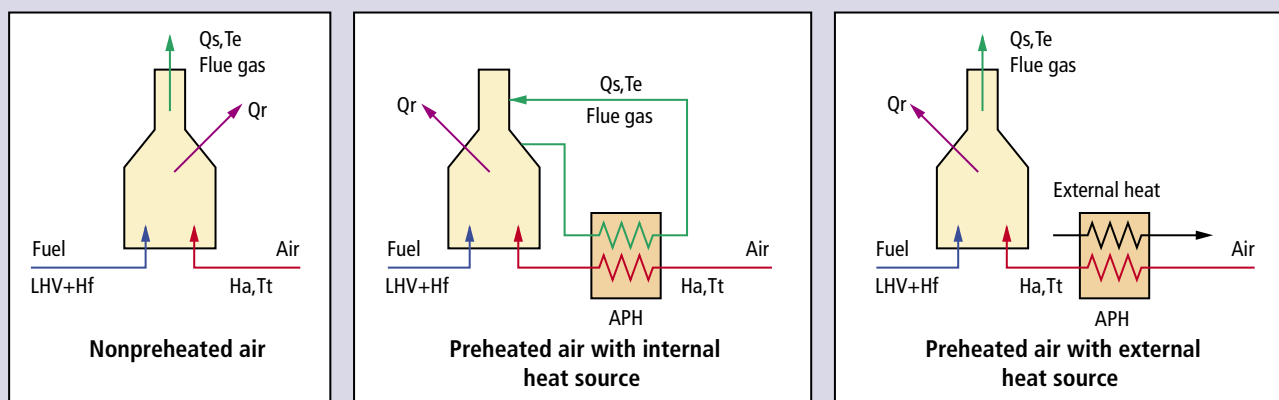$$e = \frac{(LHV + Ha + Hf) - Qs - Qr}{(LHV + Ha + Hf)} \times 100 \qquad (1)$$

FIG. 1   Eq. 1 can be used to determine the net thermal efficiency for these arrangements.
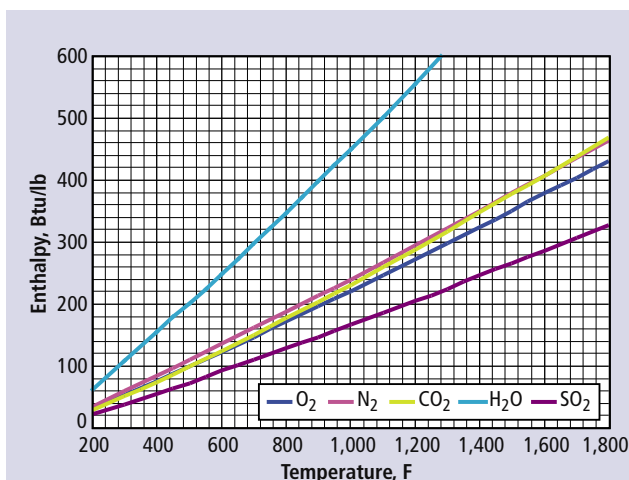
FIG. 2   Enthalpies of O_2, N_2, CO_2, H_2O and SO_2.

$$Ha = \frac{\text{lb of air}}{\text{lb of fuel}} \times Cp_{air} \times \left(Tt - Td\right)$$

$$Hf = Cp_{fuel} \times \left(Tf - Td\right)$$

where: Cp_{air} = Specific heat of air
Cp_{fuel} = Specific heat of fuel
T_t = Combustion air temperature
T_f = Fuel temperature
T_d = datum temperature (60°F).

Heat losses. Total heat loses are the sum of stack and radiation heat losses. The stack heat losses, Qs/lb of fuel, are determined from a summation of the enthalpy of the flue gas components at the stack temperature, T_e. 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:

Flue gas = Fuel + 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 H_2 requires 0.5 moles of oxygen. So, if H_2 is one of the fuel components, the volume fraction of H_2 is multiplied by 0.5 to calculate the moles of oxygen required by H_2. 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,

Theoretical moles of combustion air = Moles of oxygen × 100/21

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

Remember,

Actual moles of air = Theoretical moles of air + 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 CO_2, H_2O, SO_2, O_2 and N_2.

Hence,

Moles of flue gas components = CO_2 (Moles of CO_2 formed during combustion + Moles of CO_2 available as a fuel) + H_2O (Moles of H_2O formed during combus-

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
Qs = Calculated stack heat losses, Btu/lb of fuel
Qr = 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:

TABLE 1. Combustion reactions

Reaction	Moles of O_2 required	Moles of CO_2 formed	Moles of SO_2 formed	Moles of H_2O formed
$H_2 + 0.5O_2 \rightarrow H_2O$	0.5	0	1	0
$CO + 0.5O_2 \rightarrow CO_2$	0.5	1	0	0
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	2	1	2	0
$C_2H_6 + 3.5O_2 \rightarrow 2CO_2 + 3H_2O$	3.5	2	3	0
$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$	3	2	2	0
$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$	5	3	4	0
$C_3H_6 + 4.5O_2 \rightarrow 3CO_2 + 3H_2O$	4.5	3	3	0
$C_4H_{10} + 6.5O_2 \rightarrow 4CO_2 + 5H_2O$	6.5	4	5	0
$C_4H_8 + 6O_2 \rightarrow 4CO_2 + 4H_2O$	6	4	4	0
$C_5H_{12} + 8O_2 \rightarrow 5CO_2 + 6H_2O$	8	5	6	0
$C_6H_{14} + 9.5 O_2 \rightarrow 6CO_2 + 7H_2O$	9.5	6	7	0
$S + O_2 \rightarrow SO_2$	1	0	0	1
$H_2S + 1.5O_2 \rightarrow SO_2 + H_2O$	1.5	0	1	1
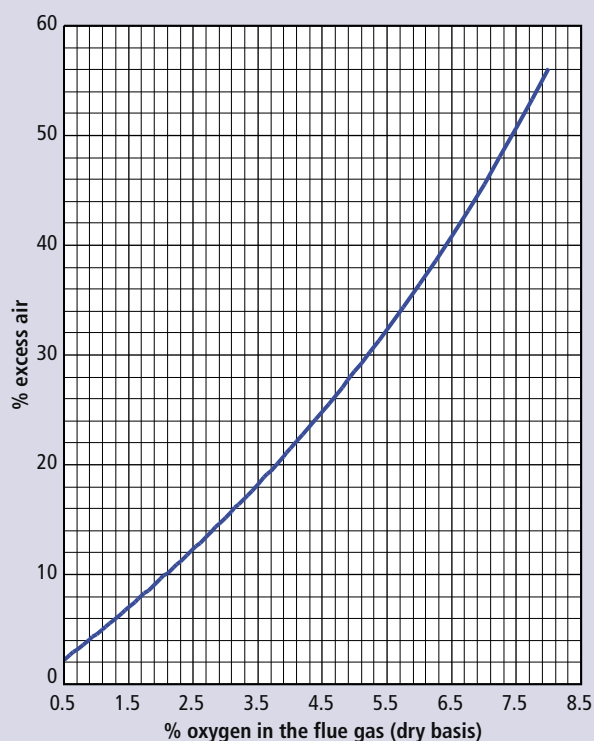
tion + Moles of H_2O *available as a fuel)* + SO_2 *(Moles of* SO_2 *formed during combustion + Moles of* SO_2 *available as a fuel)* +O_2 *(Moles of oxygen supplied – Moles of oxygen used during the combustion)* + N_2 *(Moles of* N_2 *available from air + Moles of* N_2 *available as a fuel)*

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, Qr/ 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	Syncrude 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,
Total fuel flow = 2,147.89 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 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,
Total theoretical (stoichiometric) oxygen required = 246.99 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,
Actual oxygen required = 246.99 × 1.164
= 287.50 moles/hr

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_2O 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_2H_6)	13.49	30.00	404.70	20,420	8263974	47.22	26.98	40.47	0.00
Ethylene (C_2H_4)	6.28	28.00	175.84	20,290	3567794	18.84	12.56	12.56	0.00
Propane (C_3H_8)	8.20	44.00	360.80	19,930	7190744	41.00	24.60	32.80	0.00
Propylene (C_3H_6)	5.95	42	249.90	19,690	4920531	26.78	17.85	17.85	0.00
Butane (C_4H_{10})	1.92	58	111.36	19,670	2190451	12.48	7.68	9.60	0.00
Butylene (C_4H_8)	2.06	56	115.36	19,420	2240291	12.36	8.24	8.24	0.00
Pentane (C_5H_{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_2S)	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,
Actual air required = $287.50 \times (100/21)$
= 1,369.02 moles/hr
= $1,369.02 \times 29$ (mol. wt. of air)
= 39,702 lb/hr

Actual air/lb of fuel = 39,702/2,147.89
= 18.48 lb/lb of fuel

Flue gas/lb of fuel.
Flue gas = *Fuel + Combustion air*
= 2,147.89 lb/hr + 39,702 lb/hr
= 41,850 lb/hr

Flue gas/lb of fuel = 41,850/2,147.89
= 19.48 lb/lb of fuel

Flue gas composition. From the combustion reactions shown in Table 1, each mole of CH_4 produces 2 moles of CO_2, 1 mole of H_2O and, etc.

In your combustion work sheet, multiply 36.51 (mole fraction of CH_4) by 2 (moles of CO_2) to calculate the moles of CO_2 formed in column H, etc. Repeat this step for H_2O and SO_2 and calculate the moles of H_2O and SO_2 formed in columns I and J, respectively. Total columns H, J and I.

Therefore,
Total CO_2 formed = 137.36 moles/hr
Total H_2O formed = 219.98 moles/hr
Total SO_2 formed = 0.0048 moles/hr

TABLE 3. Flue Gas Heat Loss Work Sheet

A Flue Gas component	B Moles/hr	C Mol. wt.	D (B X C) Weight, lb/hr	E Total weight/lb of fuel	F Enthalpy at 348°F	G (E X F) Heat content, Btu/lb of fuel
CO_2	137.53	44	6051.45	2.82	62	174.68
H_2O	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.
CO_2 *in the flue gas* = CO_2 *formed during combustion + CO_2 reported as a fuel*
= 137.36 moles/hr + 0.17 moles/hr
= 137.53 moles/hr

H_2O *in the flue gas* = H_2O *formed during combustion + H_2O reported as a fuel*
= 219.98 moles/hr + 0
= 219.98 moles/hr

SO_2 *in the flue gas* = SO_2 *formed during combustion + SO_2 reported as a fuel*
= 0.0048 moles/hr + 0
= 0.0048 moles/hr

O_2 *in the flue gas* = *Actual O_2 supplied – Actual O_2 used during combustion*
= 287.50 – 246.99

= 40.51 moles/hr

N_2 *in the flue gas* = N_2 *from air (moles of air − moles of oxygen) + N_2 reported as a fuel*
= (1,369.02 − 287.50) + 1.43
= 1,082.95 Moles/hr

Therefore,

Components	moles/hr	Wet basis vol%/mol%	Dry basis vol%/mol%
CO_2	137.53	9.29	10.91
H_2O	219.98	14.85	0.00
SO_2	0.0048	0.00032	0.00038
O2	40.51	2.74	3.21
N2	1,082.95	73.12	85.88
Total	**1,480.98**	**100**	**100.00**

Stack Heat Losses Qs/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 Qs at 348°F.

Therefore, Qs = 1,480.46 Btu/lb of fuel

Radiation heat loss Qr/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%.

Therefore, Qr = 20,483 × 0.025
= 512 Btu/lb of fuel

Sensible heat correction for combustion air, Ha/lb of fuel.
Ha = *lb of air/lb of fuel* × Cp_{air} × (*Tt − Td*)
= 18.48 × 0.24 × (68-60)
= 35.48 Btu/lb of fuel

Sensible heat correction for fuel Hf/lb of fuel.
H_f = Cp_{fuel} × (*Tf − Td*)
= 0.53 × (77 − 60)
= 9.01 Btu/lb of fuel

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

$$Efficiency = \frac{(20,483 + 35.48 + 9.01) - (1,480.46 - 512)}{(20,483 + 35.48 + 9.01)} \times 100$$
$$= 90.29\% \tag{1}$$

Sanjay Patel is associate process engineer, technical services, for Syncrude Canada Ltd., Canada. He has 12 years' experience in the areas of operation, technical services, process automation and controls, and projects. Mr. Patel's previous experience includes operation, troubleshooting and debottlenecking of an oxo alcohol plant and synthesis gas reformer; and commissioning and startup of world's largest grassroots refinery (Reliance Industries Ltd.) at Jamnagar, India. At Reliance worked as an assistant manager. He graduated from D.D.I.T, Gujarat University, India, and is a registered professional engineer in the province of Alberta, Canada. Mr. Patel can be contacted via e-mail at: s.patel@shaw.ca.