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. 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:

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

Therefore,

\[
e = \frac{\left(\text{LHV} + \text{Ha} + \text{Hf}\right) - \text{Qs} - \text{Qr}}{\left(\text{LHV} + \text{Ha} + \text{Hf}\right)} \times 100
\]

where:  
\(e\) = Net thermal efficiency, %
\(\text{LHV}\) = Heat input or lower heating value of the fuel, Btu/lb of fuel

**FIG. 1** Eq. 1 can be used to determine the net thermal efficiency for these arrangements.
The heat of combustion is calculated by multiplying the weight LHV.

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,

\[ \text{Moles of flue gas components} = \text{CO}_2 \times \left( \text{Moles of CO}_2 \text{ formed during combustion} + \text{Moles of CO}_2 \text{ available as a fuel} \right) + \text{H}_2\text{O} \times \left( \text{Moles of H}_2\text{O} \text{ formed during combustion} + \text{Moles of H}_2\text{O} \text{ available as a fuel} \right) + \text{SO}_2 \times \left( \text{Moles of SO}_2 \text{ formed during combustion} + \text{Moles of SO}_2 \text{ available as a fuel} \right) + \text{O}_2 \times \left( \text{Moles of oxygen supplied} - \text{Moles of oxygen used during the combustion} \right) + \text{N}_2 \times \left( \text{Moles of N}_2 \text{ available from air} + \text{Moles of N}_2 \text{ available as a fuel} \right) \]
The moles of CO₂, H₂O and SO₂ 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 the 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:**

<table>
<thead>
<tr>
<th>Heater name</th>
<th>Plant 15-1F-1 (hydrogen heater)</th>
<th>Syncrude Canada Ltd., Fort McMurray, Canada</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flue gas exit temperature, °F</td>
<td>348</td>
<td></td>
</tr>
<tr>
<td>Ambient air temperature</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Combustion air temperature, °F</td>
<td>68</td>
<td></td>
</tr>
<tr>
<td>Fuel gas temperature, °F</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>Oxygen in the flue gas, vol.%</td>
<td>3.2 (dry basis)</td>
<td></td>
</tr>
<tr>
<td>Assumed radiation losses, %</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>

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:

1. 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, 
   $\text{Total fuel flow} = 2,147.89 \text{ lb/hr}$

2. 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, 
   $\text{LHV} = 20,483 \text{ Btu/lb of fuel}$

**Combustion air/lb of fuel.** From the combustion reactions shown in Table 1, each mole of CH₄ requires 2 moles of O₂, etc.

In your combustion work sheet, multiply 36.51 (CH₄ mol fraction in column B) by 2 (moles of oxygen) to calculate theoretical or stoichiometric oxygen required for CH₄ in column G and so on. Then total column G on the total line to obtain the quantity of total oxygen required.

Therefore, 
$\text{Total theoretical (stoichiometric) oxygen required} = 246.99$ 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, 
$\text{Actual oxygen required} = 246.99 \times 1.164$  
$= 287.50$ moles/hr

Air is 21% oxygen by volume,

Therefore, 
$\text{Actual air required} = 287.50 \times (100/21)$  
$= 1,369.02$ moles/hr
**TABLE 2. Combustion work sheet**

<table>
<thead>
<tr>
<th>Fuel Component</th>
<th>Vol. fraction, (moles/hr)</th>
<th>Mol. wt.</th>
<th>Total weight (lb/hr)</th>
<th>Net heating value, Btu/lb</th>
<th>Heating value, Stoichiometric oxygen required, moles/hr</th>
<th>CO₂ formed during combustion, moles/hr</th>
<th>H₂O formed during combustion, moles/hr</th>
<th>SO₂ formed during combustion, moles/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (CH₄)</td>
<td>36.51</td>
<td>16.00</td>
<td>584.16</td>
<td>21,500</td>
<td>12559440</td>
<td>73.02</td>
<td>36.51</td>
<td>0.00</td>
</tr>
<tr>
<td>Hydrogen (H₂)</td>
<td>22.80</td>
<td>2.00</td>
<td>45.60</td>
<td>51,600</td>
<td>2352960</td>
<td>11.40</td>
<td>0.00</td>
<td>22.80</td>
</tr>
<tr>
<td>Ethane (C₂H₆)</td>
<td>13.49</td>
<td>30.00</td>
<td>404.70</td>
<td>20,420</td>
<td>8263974</td>
<td>47.22</td>
<td>26.98</td>
<td>40.47</td>
</tr>
<tr>
<td>Ethylene (C₂H₄)</td>
<td>6.28</td>
<td>28.00</td>
<td>175.84</td>
<td>20,290</td>
<td>3567794</td>
<td>18.84</td>
<td>12.56</td>
<td>12.56</td>
</tr>
<tr>
<td>Propane (C₃H₈)</td>
<td>8.20</td>
<td>44.00</td>
<td>360.80</td>
<td>19,930</td>
<td>7190744</td>
<td>41.00</td>
<td>24.60</td>
<td>32.80</td>
</tr>
<tr>
<td>Propylene (C₃H₆)</td>
<td>5.95</td>
<td>42</td>
<td>249.90</td>
<td>19,690</td>
<td>4920531</td>
<td>26.78</td>
<td>17.85</td>
<td>17.85</td>
</tr>
<tr>
<td>Butane (C₄H₁₀)</td>
<td>1.92</td>
<td>58</td>
<td>111.36</td>
<td>19,670</td>
<td>2190451</td>
<td>12.48</td>
<td>7.68</td>
<td>9.60</td>
</tr>
<tr>
<td>Butylene (C₄H₈)</td>
<td>2.06</td>
<td>56</td>
<td>115.36</td>
<td>19,420</td>
<td>2240291</td>
<td>12.36</td>
<td>8.24</td>
<td>8.24</td>
</tr>
<tr>
<td>Pentane (C₅H₁₂)</td>
<td>0.44</td>
<td>72</td>
<td>31.68</td>
<td>19,500</td>
<td>617760</td>
<td>3.52</td>
<td>2.20</td>
<td>2.64</td>
</tr>
<tr>
<td>Nitrogen (N₂)</td>
<td>1.43</td>
<td>28</td>
<td>40.44</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>0.74</td>
<td>28</td>
<td>20.80</td>
<td>4,345</td>
<td>90393</td>
<td>0.37</td>
<td>0.74</td>
<td>0.00</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>0.17</td>
<td>44</td>
<td>7.48</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>Hydrogen sulfide (H₂S)</td>
<td>0.0048</td>
<td>34</td>
<td>0.16</td>
<td>6,550</td>
<td>1069</td>
<td>0.01</td>
<td>0.00</td>
<td>0.0048</td>
</tr>
</tbody>
</table>

**Total/lb of fuel**

|   | 100.00 | 2,147.89 | 43,995,407 | 246.99 | 137.36 | 219.98 |

\[
= 1,369.02 \times 29 \text{ (mol. wt. of air)}
\]

\[
= 39,702 \text{ lb/hr}
\]

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

**Flue gas/lb of fuel.**

\[
\text{Flue gas} = \text{Fuel} + \text{Combustion air}
\]

\[
= 2,147.89 \text{ lb/hr} + 39,702 \text{ lb/hr}
\]

\[
= 41,850 \text{ lb/hr}
\]

\[
\text{Flue gas/lb of fuel} = \frac{41,850}{2,147.89} = 19.48 \text{ lb/lb of fuel}
\]

**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,

\[
\begin{align*}
\text{Total CO₂ formed} & = 137.36 \text{ moles/hr} \\
\text{Total H₂O formed} & = 219.98 \text{ moles/hr} \\
\text{Total SO₂ formed} & = 0.0048 \text{ moles/hr}
\end{align*}
\]

**Flue Gas.**

\[
\begin{align*}
\text{CO₂ in the flue gas} & = \text{CO₂ formed during combustion} + \text{CO₂ reported as a fuel} \\
& = 137.36 \text{ moles/hr} + 0.17 \text{ moles/hr} \\
& = 137.53 \text{ moles/hr}
\end{align*}
\]

**TABLE 3. Flue Gas Heat Loss Work Sheet**

<table>
<thead>
<tr>
<th>A</th>
<th>B Moles/hr</th>
<th>C Mol. wt.</th>
<th>D (B X C)</th>
<th>E Total weight/lb of fuel</th>
<th>F Enthalpy at 348°F</th>
<th>G (E X F)</th>
<th>Heat content, Btu/lb of fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>137.53</td>
<td>44</td>
<td>6051.45</td>
<td>2.82</td>
<td>62</td>
<td>174.68</td>
<td></td>
</tr>
<tr>
<td>H₂O</td>
<td>219.98</td>
<td>18</td>
<td>3959.73</td>
<td>1.84</td>
<td>128</td>
<td>235.97</td>
<td></td>
</tr>
<tr>
<td>SO₂</td>
<td>0.0048</td>
<td>64</td>
<td>0.31</td>
<td>0.0001</td>
<td>44</td>
<td>0.0063</td>
<td></td>
</tr>
<tr>
<td>O₂</td>
<td>40.51</td>
<td>32</td>
<td>1296.20</td>
<td>0.60</td>
<td>65</td>
<td>39.23</td>
<td></td>
</tr>
<tr>
<td>N₂</td>
<td>1082.96</td>
<td>28</td>
<td>30322.83</td>
<td>14.12</td>
<td>73</td>
<td>1030.58</td>
<td></td>
</tr>
</tbody>
</table>

Total 1480.98 1480.46

H₂O in the flue gas = H₂O formed during combustion + H₂O reported as a fuel = 219.98 moles/hr + 0 = 219.98 moles/hr

SO₂ in the flue gas = SO₂ formed during combustion + SO₂ reported as a fuel = 0.0048 moles/hr + 0 = 0.0048 moles/hr

O₂ in the flue gas = Actual O₂ supplied - Actual O₂ used during combustion = 287.50 - 246.99 = 40.51 moles/hr

N₂ in the flue gas = N₂ from air (moles of air - moles of oxygen) + N₂ reported as a fuel = (1,369.02 - 287.50) + 1.43 = 1,082.95 Moles/hr
Therefore,

<table>
<thead>
<tr>
<th>Components</th>
<th>moles/hr</th>
<th>Wet basis vol%/mol%</th>
<th>Dry basis vol%/mol%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>137.53</td>
<td>9.29</td>
<td>10.91</td>
</tr>
<tr>
<td>H₂O</td>
<td>219.98</td>
<td>14.85</td>
<td>0.00</td>
</tr>
<tr>
<td>SO₂</td>
<td>0.0048</td>
<td>0.00032</td>
<td>0.00038</td>
</tr>
<tr>
<td>O₂</td>
<td>40.51</td>
<td>2.74</td>
<td>3.21</td>
</tr>
<tr>
<td>N₂</td>
<td>1,082.95</td>
<td>73.12</td>
<td>85.88</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,480.98</strong></td>
<td><strong>100</strong></td>
<td><strong>100.00</strong></td>
</tr>
</tbody>
</table>

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.

\[ Ha = \frac{lb \text{ of air}/lb \text{ of fuel} \times C_p_{air} \times (T_f - T_d)}{34.88} \]

Sensible heat correction for fuel Hf/lb of fuel.

\[ H_f = \frac{C_p_{fuel} \times (T_f - T_d)}{34.88} \]

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

\[ \text{Efficiency} = \frac{20,483 + 35.48 + 9.01}{20,483 + 35.48 + 9.01} \times 100\% = 90.29\% \]

LITERATURE CITED

2 API recommended practice 533.

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 oxy 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.

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