Determination of Industrial Boiler Temperature Profile for Oil and Gas Fuels

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ABSTRACT
Industrial boilers firing oil or gas with heat input of more than 100 MMBtu/hr are commonly used in a wide range of industrial applications. Their temperature profile is an essential design parameter allowing engineers build boilers with compact size with pertinent heat transfer areas for all boiler components including furnace, superheater, boiler bank tubes, and economizer. Determination of boiler temperature profile is a tedious task requiring knowledge of combustion details, heat transfer modes, heat transfer areas, and boiler operational modes. The profile includes boiler furnace exit temperature of flue gases leaving the furnace through screen tubes, temperature downstream screen tubes, superheater exit temperature, economizer inlet temperature, and stack temperature. This paper describes procedural approach in determining temperature profile across a boiler to assist in providing accurate boiler design as well as continuously monitoring of boiler operation for reliable operation assurance in industrial facilities.

INTRODUCTION
Boilers are designed with a typical temperature profile through their components. Boiler furnace being the first component containing combustion heat is designed with limited heat liberation and heat flux resulting in maximum temperatures at the furnace exit for different boiler loads. Monitoring boiler furnace exit temperatures and maintaining them below maximum temperatures insures appropriate combustion within the furnace and negates furnace tube overheating. Downstream of the furnace temperature is the temperature of the boiler screen tubes exit, whose monitoring indicates condition of the screen tubes. Then temperature downstream of the superheater gives indication of the superheater operational condition. Similarly, temperatures downstream boiler bank tubes and economizer indicate condition of boiler bank tubes and economizer respectively. Figure No. 1 shows locations of temperatures in a typical industrial boiler.

TEMPERATURE PROFILE
The following temperatures are calculated in the boiler:

- Furnace exit temperature.
- Temperature downstream of screen tube.
- Temperature downstream of superheater.
- Temperature downstream of boiler bank tubes.
- Temperatures downstream of economizer.

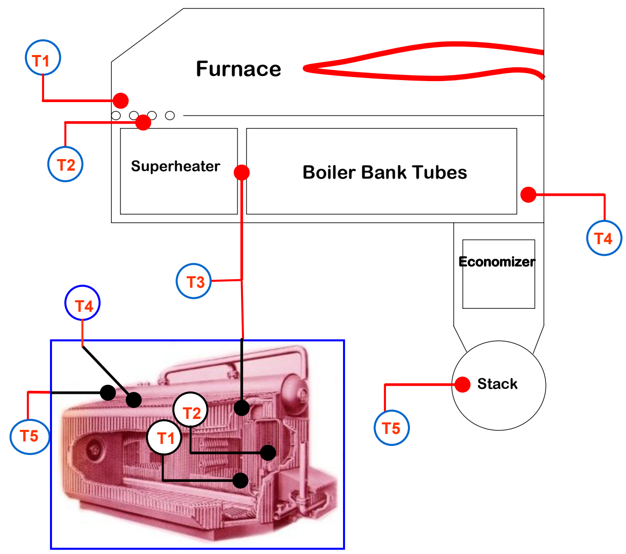

Figure No. 1: Temperature Profile across boiler components

Above temperatures have different values at different loads making their values of a dynamic nature dependant on boiler load. Furnace exit temperature is calculated from the flue gas interaction with the furnace heat transfer areas and the amount of radiation involved. Flue gas properties such as moisture percentage play a role in the flue gas heating value affecting the amount of the furnace exit temperature.

Temperature across screen tubes is the direct temperature drop resulting from heat exchange between flue gas and water inside screen tubes. Similarly, temperatures downstream of superheater, boiler bank tubes, and economizer are obtained from direct heat transfer between flue gas and these component internal fluids.

TEMPERATURE PROFILE CALCULATIONS

1. Furnace Exit Temperature Calculations (t_1):
Calculations of furnace gas exit temperature can be performed for one condition and that without flue gas recirculation (FGR).

Exit temperature can be calculated by knowing the gas sensible heat which is determined by the following equation.

$$H_{fuel+air} = [HHV - C (M_P-M_f)/UW_g]+[0.24*UW_a (t_{10}-t_9)/UW_g] \quad (1)$$

Where,

C = 1030 for solid and liquid fuels
= 1060 for gaseous fuels.

The above equation calculates the sensible heat in the gas by excluding the heat required to keep the moisture in a gaseous state from the higher heating value of the fuel in addition to the heat in the air entering the boiler. If air is not heated then $t_{10}= t_9$ and the right term in the equation reduces to zero.

Also another term should be calculated; this term is

$$W_g/Sr \quad (2)$$

The Sr is defined as the surface that "sees" the flame and therefore receives radiant heat from the flue gas and reducing its temperature. The Sr value can be calculated from the following equation:

$$Sr = \pi/2 * (EPRS) \quad (3)$$

After calculating the Sr value then it is used in a chart in conjunction with the sensible heat to look up the furnace exit temperature from Figure No. 2.

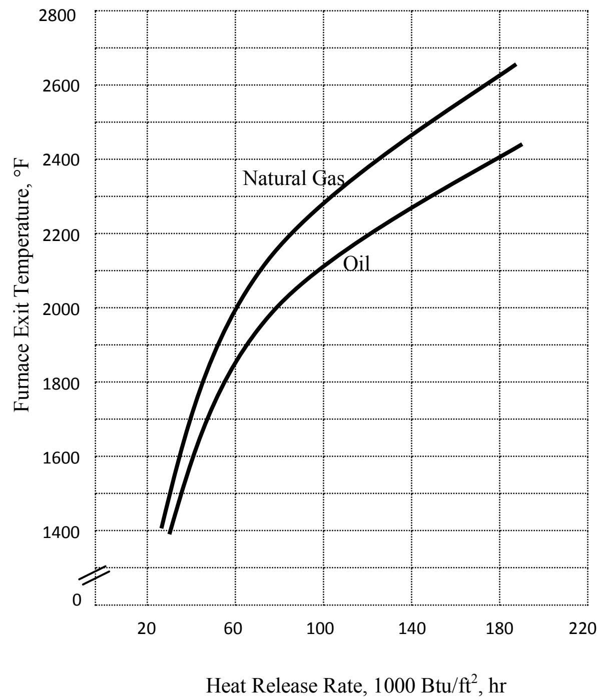

Figure No. 2: Approximate relationships of furnace exit temperature to heat release rate for oil and natural gas

2. Temperature Downstream of Boiler Screen Tubes (t_2):
After calculating the furnace gas exit temperature, then temperature downstream of the screen tubes is calculated. This temperature, t_2, is calculated by the following equation:

$$t_2 = (t_1 - W_g/Sr) \text{ (rounded off to the nearest 5° F but not exceed 100° F)} \quad (4)$$

The above equation is empirical equation produced from experience in design and testing of industrial boilers.

The t_2 temperature may be considered the superheater flue gas inlet temperature if the superheater lies directly behind the screen tubes, however, if not, boiler bank tubes upstream of the superheater if any would have an effect on the temperature by reducing its value. A temperature downstream of the boiler bank tubes has to be calculated to obtain the flue gas temperature in this case.

3. Temperature Downstream of Superheater (t_3)

The first step in the design of a superheater is to assume the temperature leaving the superheater, t_3. Then, an average temperature across the superheater is calculated as follows:

$$t_{avg} = (t_2+t_3)/2 \quad (5)$$

Then a Δt across the superheater is calculated using the following equation:

$$\Delta t = (W_s * \Delta Hs'tr)/(W_g * C_g) \quad (6)$$

Where,

A heat loss to the surrounding of 7.5% of Δt should be considered when calculating t_3 as shown in the equation below:

$$t_3 = t_2 - [\Delta t + (7.5\% * \Delta t)] \quad (7)$$

The calculated result of t_3 is compared with the assumed value. If the calculated results are close to the assumed value the calculated value is considered, and if not, iteration is performed to obtain more accurate values.

4. Determination of Temperature downstream of boiler Bank tubes (t_4)

The first step is to assume a temperature t_4, and then an average temperature is calculated as follows:

$$t_{avg} = (t_3+t_4)/2 \quad (8)$$

Then a wall temperature t_w is determined by the equation below:

$$t_w = t_s + 50 \quad (9)$$

Similarly, a film temperature t_f is calculated by the equation below:

$$t_f = (t_{avg}+t_w)/2 \quad (10)$$

Given all of the above information, the heat transfer rate Rc and R are calculated from the equations below:

$$Rc = 0.261 * F_d * F_a * (G^{0.6}/d_o^{0.4}) * (k/\mu^{0.6}) * (Cp*\mu/k)^{1/3} \quad (11)$$

Where,

F_a= 1,

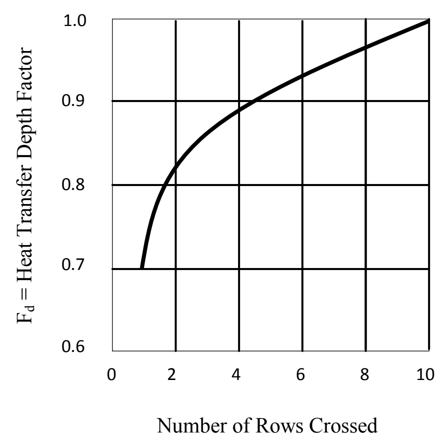

Figure No. 3: Heat Transfer depth factor for number of tube rows crossed in convection banks

F_d can be looked up in Figure No. 3.

$$R = Rc/(1-K*Rc) \text{ (corrected for dirt)} \quad (12)$$

Where,

K= 0.005 for natural gas firing.
= 0.01 for oil firing.

Intertube non-luminous gas radiation (r) from CO_2 and H_2O is approximated to be 20% of the R value, Therefore, the total heat transfer rate for boiler bank tubes is calculated as follows:

$$U = (R+r) = 1.2\ R \quad (13)$$

Then calculate the boiler bank tube heating surface area Sc from the total number of tubes within the boiler banks and the following relation can be obtained:

$$X = \frac{U*S_c}{W_g*C_g} \quad (14)$$

$$t'_4 = t_s + \frac{t_3-t_s}{e^x} \quad (15)$$

$$t_4 = t'_4 + \text{service factor average} \quad (16)$$

The surface factor average is as follows:

For natural gas = -10 °F.
For oil = -5 °F.

5. Determination of Temperature downstream economizer (t_5):

Temperature downstream economizer can simply and directly be calculated as all terminal temperature like boiler feed water, steam drum saturation temperature, t_4 and boiler and gas flow rates are also known. The calculation involves direct heat exchange procedure.

NOMENCLATURE

HHV=Higher heating value Btu/lb
M_P= Moisture produced from combustion lb.
M_f= Moisture in fuel in liquid form lb/lb of fuel.
UW_g= Unit gas weight lb/lb of fuel.
UW_a= Unit air weight lb/bl of fuel.
t_1= Furnace exit temperature °F
t_2= Temperature downstream screen tubes °F.
t_3= Superheater flue gas outlet temperature °F.
t_4= Boiler Bank tubes outlet temperature °F.
t_5 = Economizer outlet temperature, °F.
t_9= Ambient temperature °F.
t_{10}= Air temperature entering furnace °F
F_d = Depth factor
F_a = Arrangement factor
G = Gas flow rate, lb/hr. ft^2
k = Gas thermal conductivity @ t_f ,
μ = Gas viscosity @ t_f
Cp = Specific heat @ t_f
t_s = Saturated steam temperature, °F.
t_w = Water temperature, °F.
t_f = Film temperature, °F.
t_{avg} = Average temperature, °F.
Ws= Steam flow rate, lb/hr.
Δ Hs'tr =Superheater heat duty, Btu/lb.
W_g = Flue gas weight, lb/hr.
C_g =Specific heat of flue gas at t_{avg}
EPRS=effective projected radiant surface, ft^2
Sr = radiant surface, ft^2.
S_L = Transverse tube pitch, in
S_T = Longitudinal tube pitch, in
do = Outside tube diameter, in
Sc = boiler bank tube heating surface area, ft^2
Δt =Temperature across superheater, °F.
K = Correction factor.
R = Heat transfer rate, Btu/ft^2. °F. hr.
Rc = Heat transfer rate, Btu/ft^2. °F. hr.
r = Intertube heat transfer rate, Btu/ft^2. °F. hr.
U = Total heat transfer rate, Btu/ft^2. °F. hr.

CONCLUSION

Boiler temperature profile including boiler furnace exit temperature of flue gases leaving the furnace through screen tubes, temperature downstream screen tubes, superheater exit temperature, economizer inlet temperature, and stack temperature were calculated in this paper with a clear procedural approach.

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