Lecture 38: Industrial Furnaces

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What is a furnace?

A furnace is essentially a thermal enclosure and is employed to process raw materials at high temperatures both in solid state and liquid state. Several industries like iron and steel making, non ferrous metals production, glass making, manufacturing, ceramic processing, calcination in cement production etc. employ furnace. The principle objectives are

a) To utilize heat efficiently so that losses are minimum, and

b) To handle the different phases (solid, liquid or gaseous) moving at different velocities for different times and temperatures such that erosion and corrosion of the refractory are minimum.

Source of energy

a) Combustion of fossil fuels, that is solid, liquid and gaseous.
b) Electric energy**:** Resistance heating, induction heating or arc heating.
c) Chemical energy**:** Exothermic reactions

Types of furnaces:

Furnaces are both batch and continuous type. In the continuous type for example in heating of ferrous material for hot working, the furnace chamber consists of preheating, heating and soaking zones. The material enters through the preheating zone and exits the soaking zone for rolling. But the flow of products of combustion is in the reverse direction. Furnace design is recuperative type in that material exits at the desired temperature from the soaking zone and the products of combustion discharge the preheating zone at the lowest possible temperature. Different types of continuous furnaces are in use, like walking beam type, pusher type, roller hearth type, screw conveyor type etc.

In the batch furnaces, the load is heated for the fixed time and then discharged from the furnace. There are different types of batch furnaces like box type, integral quench type, pit type and car.

In many cases the furnace is equipped with either external heat recovery system or internal heat recovery system. In the external heat recovery system a heat exchanger like recuperator is installed outside the furnace. Here heat exchanger must be integrated with the furnace operation. In the internal heat recovery the products of combustion are recirculated in the furnace itself so that flame temperature is somewhat lowered. The objective is to reduce the NO_x formation ottom type

How thermal energy is obtained from fossil fuel?

All fossil fuel contain potential energy. On combustion potential energy is released in the products of combustion. The products of combustion exchange energy with the sink to raise its temperature to the required value and then exit the system. The sensible heat in POC at the critical process temperature is not available to the furnace. The higher the process critical temperature higher would be the sensible heat in POC. This sensible heat in POC is very important from the point of view of fuel utilization. We define gross available heat (GAH) as

$$\text{GAH} = \text{Calorific value of fuel} + \text{sensible heat of reactants} - \text{Heat carried by POC} \quad 1)$$

GAH represents the heat available at the critical process temperature; it may not represent heat available to perform a given function due to the various types of losses. GAH may be used as a criterion for comparing different fuel-combustion system.

Once the furnace is designed and built, the heat losses are not within the control of the operator; it is governed by the process critical temperature, refractory lining thickness and thermal conductivity of the refractory. Defining net available heat (NAH) as

$$\text{NAH} = \text{GAH} - \text{Heat losses} \qquad 4)$$

NAH can be used as a criterion for comparing the smelting/melting/heating efficiency of different furnaces.

Variables affecting heat utilization

For a given furnace design and the daily heat requirements, GAH is fixed and it is required to supply this much of heat on per day basis, we can calculate

$$\text{Fuel consumption} = \frac{\text{Required GAH per unit of time}}{\text{GAH per kg of fuel}} \qquad 5)$$

If heat supply is the critical factor in determining the process throughput then GAH can not determine the throughput, we have to consider the NAH

$$\text{Furnace throughput} = \frac{\text{NAH generated per unit of time}}{\text{Required NAH per unit of throughput}} \qquad 6)$$

Heat utilization or fuel utilization according to equation 5 is inversely proportional to GAH/kg of fuel. We can derive the factors affecting heat utilization by considering eq.1

Air adjustment: Calorific value (CV) of fuel is the energy obtained on complete combustion of fuel with theoretical amount of air. Excess air, air leakage, furnace draft, fuel/air ratio will control the fuel consumption

Sensible heat of reactant; this heat directly adds to the furnace, fuel consumption will decrease.

POC temperature: an increase in POC temperature will increase fuel consumptionIncomplete combustion or un-burnt fuel; corresponding to incomplete combustion part of the CV of the fuel is lost with the products of incomplete combustion

Heat Utilization: Concepts

Efficient utilization of fossil fuel reserves requires, in addition to other factors, utilization of heat of POC exiting the furnace. It is well known that potential energy of fuel at 25°C on combustion is converted into the sensible heat pf products of combustion at the flame temperature. Products of combustion after transferring their heat to the furnace chamber exit the furnace. Heat carried by products of combustion depends on the temperature of the furnace; higher is the furnace temperature higher is the amount of heat carried by POC. It may range somewhere in between 40 to 60% of the calorific value of fuel. Heat of POC can be recovered either external to the furnace by installing a heat exchanger or internally by recirculating the POC into the flame in the furnace itself. The former is called external heat recovery and the later is internal heat recovery.

In the following we discuss the principles of external heat recovery of POC. Normally a heat exchanger is integrated with the furnace which captures and reuses the heat of POC simultaneously.

Thermodynamic principles of capture and re-use of heat of POC:

Capture and re-use of heat of POC must be integrated. A heat exchanger integrates capture and reuse of heat. In the heat exchanger hot fluid (POC) flows co-current or counter-current to cold fluid, say air. Both fluids are separated by a wall. Hot fluid enters the heat exchanger at temperature T_{h1} and exits at temperature T_{h2} ($T_{h2} < T_{h1}$). Wall is heated by the heat transferred from the hot POC. Cold fluid enters the heat exchanger at temperature T_{c1} and leaves at T_{c2} such that $T_{c2} > T_{c1}$.

Heat balance over an infinitesimally small element of length dx can be written at steady state

Heat lost by hot fluid = Heat gained by the cold fluid − Heat loss from the element to the surrounding 1)

Let m_h, and m_c are mass of hot fluid and cold fluid, C_{Ph} and C_{Pc} are the specific heat of hot and cold fluid then we can write

$$m_h \text{ x } C_{Ph} \text{ x } dT_h = m_c \text{ x } C_{Pc} \text{ x } dT_c - dQ \qquad 7)$$

In eq. 2 dT_h and dT_c are the change in temperatures of hot and cold fluid at any position along the length of the exchanger.

In an ideal adiabatic-reversible heat exchange between hot and cold fluid, dQ = zero and the process is reversible when temperature difference between hot and cold fluid at any position along the length of the heat exchanger, i.e.$\Delta T_i = (dT_{hi} - dT_{ci}) = 0$ provided

$m_h \text{ x } C_{Ph} = m_c \text{ x } C_{Pc}$.

This is possible when both fluids have infinite contact time, and separating wall has zero thermal resistance. In this situation the temperature difference between hot and cold fluid at any position will be very small and constant along the length of the heat exchanger.

Finite thermal resistance of the separating wall and flow rates of both fluids make the heat exchange irreversible. Finite flow rates of both fluids will have finite residence time depending on flow rates and as a result all the heat is not transferred from hot to cold fluid. Similarly finite thermal resistance of the wall will also limit the transfer of heat to the cold fluid. In such a situation for an adiabatic process .ΔT_i = $(dT_{hi} - dT_{ci})$ will be non-zero, but will have constant value when $m_h \times C_{Ph} = m_c \times C_{Pc}$.

The practical result of the irreversibility is that the heat exchange is not complete and there is always some heat which is left with the POC on leaving the heat exchanger.

Difference in heat capacities of fluid will influence the heat exchange process. For example if $C_{Ph} > C_{Pc}$, cold fluid can be heated nearly to the entering temperature of hot fluid provided $m_h = m_c$.

Efficiency of heat exchangers

Thermodynamically thermal resistance of the wall, heat leaving the exchanger with POC influences the thermal efficiency of the heat exchanger.

$$\text{Overall thermal efficiency} = \frac{100 \text{ x Sensible heat in preheated air}}{\text{Sensible heat in flue gas}} \qquad 8)$$

According to the definition of overall thermal efficiency, it appears that the air can be preheated to the temperature above the flue gas temperature since no upper limit is assigned to the temperature of the preheated air temperature. Thermodynamically, in heat exchange between hot flue gas and cold air, air can not be preheated to the temperature above the flue gas temperature.

$$\text{Efficiency limit} = \frac{100 \text{ x Sensible heat in air at hot flue gas temperature}}{\text{Sensible heat in hot flue gas}} \qquad 9)$$

$$\text{Relative efficiency} = \frac{100 \text{ x Overall thermal efficiency}}{\text{efficiency limit}} \qquad 10)$$

$$\text{Relative efficiency} = \frac{100 \text{ x Sensible heat in preheated air}}{\text{Sensible heat in air at hot flue gas temperature}} \qquad 11)$$

Consider a heat exchanger which receives hot flue gas at 1600K and cold air at 298K. The hot flue gases leave the exchanger at 900K and cold air at 1373K. About 15% of the heat in flue gases is lost to the surroundings. The ratio of specific heat of flue gas to air is 1.2. Calculate the various efficiencies.

Heat balance gives $\frac{m_c\, Cp_c}{m_h\, Cp_h}$ = 0.55

Overall thermal efficiency by equation 8 is 45.4%

Efficiency limit by equation 9 is 55% and relative efficiency by equation 10 or 11 is 82.5%

Illustration

Regenerator receives hot flue gases at $1400°C$ and cold air at $25\ °C$, the flue gases leave at $750\ °C$ and the air is preheated to $1100°C$. As estimated 15% of the heat given up by the flue gases is heat lost to the regenerator surroundings, and the rest (85%) is recovered in the preheated air. It may be assumed for estimating purposes that $C_P = 0.3$ for flue gases and $C_P = 0.25$ for air, independent of temperature. **Estimate over all thermal efficiency, efficiency limit, and relative efficiency for this heat exchange operation.**

Suppose now that the depth of the regenerator is increased to 2.5 times in such a way to double the heat exchange area while keeping constant the over-all heat transfer coefficient $U\left(\frac{Btu}{hr\ ft^2 °F}\right)$.The quantities and entering temperatures of the flue gases and air will be kept the same. Heat losses are same as that in a). **Estimate for the enlarged regenerator (a) air preheat temperature, (b) over-all thermal efficiency and relative thermal efficiency**

Solution:

a) Heat balance: reference temperature 25°C

$$m_a C_{P_a}(1100 - 25) = 0.85\ m_f\ C_{P_f}\ (1400 - 750)$$

$$\frac{m_a C_{Pa}}{m_f\ C_{P_f}} = 0.514$$

Overall thermal efficiency $= 40.18\%$.

Efficiency limit $= 51.4\%$.

Relative efficiency $= 79.4\%$.

b) Air preheat temperature and exit temperature of flue gas are not known. Since quantities and entering temperatures of flue gas and air are same. We can write

$$\ln\left[\frac{T_{h_2} - 25}{1400 - T_{c_2}}\right] = 2.5 \times \ln\left[\frac{750 - 25}{1400 - 1100}\right]$$

$$T_{h_2} - 25 = 12698 - 9.07 T_{c_2} \qquad (1)$$

Heat balance for the enlarged regenerator:

$$m_a\ C_{P_a}\left(T_{c_2} - 25\right) = 0.85\ m_f\ C_{P_f}\left(1400 - T_{h_2}\right) \qquad (2)$$

In equation 2, T_{c_2} and T_{h_2} are air and flue gas temperature at the exit of the regenerator.

Or $0.605\ T_{c_2} - 15.11 = 1400 - T_{h_2}$ (3)

By solving 1 and 3

We get $T_{c_2} = 1335.8°C$ and $T_{h_2} = 557°C$.

Overall thermal efficiency = 49 %.

Relative efficiency = 96 %.