Lecture 39: Industrial furnaces

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Exercise-I

An oil fired reheating furnace consumes 100 Kg/ hr oil to heat 1 ton billet to 1400 K. Oil analyses $86\ \%\ \mathrm{C}$ and $14\ \%\ \mathrm{H}$ and is burnt with 25% excess air. Gross calorific value of oil is 45000 kJ/kg. The POC exits the furnace at 1500 K. What are the heat losses & thermal efficiency?

Solution:

Heat balance:

Heat input = Heat carried by POC + Heat carried by steel +Heat losses.

We can calculate amount of POC / 100 kg fuel and heat to POC. All the sensible heat values are taken from the reference given at the end of this lecture. Heat to POC$= 3.11\ \times 10^6\ \mathrm{kJ/hr}$.

Heat to steel$= 0.7\ \times 10^6\ \mathrm{kJ/hr}$.

Heat input $= 4.5\ \times 10^6\ \mathrm{kJ/hr}$.

Heat losses$= 0.63\ \times 10^6\ \mathrm{kJ/hr}$.

Thermal efficiency $= 16.8\ \%$ which means that $16.8\ \%$ of the calorific value of fuel is used in heating billet.

For this furnace let us install a preheater which can recover 50% of heat to preheat air. Heat losses and heat to steel are unchanged. Calculate the carbon offset due to preheater.

Preheater installation results in fuel saving. Let $\mathrm{F\,kg/hr}$ is now fuel required. Heat balance

$$\mathrm{F} \times 0.5\ \times 31144 + 45000\mathrm{F} = 0.63\ \times 10^6 +\ 0.76\ \times 10^6 +\ 31144\mathrm{F}.$$

$$F = 47\ \text{kg/hr.}$$

Saving in fuel $= 53\,\text{kg/hr.}$

For 20 hr/day and 25 days in month

Fuel saving $= 26500\,\text{kg/month}$

Exercise-II

$30\ m^3/hr$ of natural gas is burned in a remelting furnace, which operates 24 hours/day, 300 days in a year. The natural gas analyses 70% CH_4 and 30% C_2H_6. Dry combustion air is 20% excess than theoretical requirements. Flue gas enters the stack at $1200K$. Volumes are given at $25°C$ and 1 atmospheric pressure.

It is proposed to install a preheater which will cool the flue gases from $1200K$ to $800K$. It may be assumed that 90% of the heat recovered from flue gases is transferred to air. Calculate annual fuel saving resulting due to preheater installation. Also calculate carbon affect generation.

The heat of combustion values are:

$$-\Delta H_f^\circ\, CO_2 = 97.2 \times 10^3\ \text{k cal (kg mole)}^{-1}$$

$$-\Delta H_f^\circ\, H_2O\ (V) = 57.8 \times 10^3\ \text{k cal (kg mole)}^{-1}$$

$$-\Delta H_f^\circ\, CH_4 = 17.89 \times 10^3\ \text{k cal (kg mole)}^{-1}$$

$$-\Delta H_f^\circ\, C_2H_6 = 20.24 \times 10^3\ \text{k cal (kg mole)}^{-1}$$

And sensible heat in POC is

POC	H_{1200}-H_{298} {Kcal (kg mole)$^{-1}$}	H_{800}-H_{298}{Kcal (kg mole)$^{-1}$}
CO_2	10650	5458
$H_2O(V)$	8217	4403
O_2	7040	3786
N_2	6728	3600

Solution: solution is given in brief**.**

Heat of combustion for the reaction

$$CH_4 + 2O_2 = CO_2 + 2\ H_2O_{(v)}\ .$$

$C_2H_6 + 3.52O_2 = 2\ CO_2 + 3\ H_2O_{(v)}$.

$\Delta H^{\circ}_{Comb,} = 296434$ k cal.

Heat transferred to air $= 0.9[(H_{1200} - H_{298})_{POC} - (H_{800} - 298)_{POC}]$.

Heat transferred to air $= 0.9[\{8281 + 10763 + 1956 + 42425\}]$

$= 57082$ k cal.

Fuel saving $= 0.236$ kg mole/hr.

1kg mole $= 24.45\ m^3$ (1 atmosphere and 298K)

Fuel saving/Year $\approx 41550\ m^3 = 19\%$.

Now fuel saving/Year will lead to reduction in CO_2 which is equal to 2208 kg moles

Exercise-III

Consider combustion of fuel oil with air to heat the furnace to a temperature at T^oC Fuel oil analyses 84% C 5% H 2% S and 9% incombustibles. Gross calorific value of fuel oil is 9500 kcal/kg. Determine GAH in each case when the furnace temperature T is a) 727^oC b) 827^oC c) 927^oC and d 1127^oC Assume complete combustion with the theoretical amount of air

Solution

GAH in kcal = calorific value of fuel − Heat to POC

Basis of calculation is 1 kg fuel. Reference state of H_2O in POC is liquid and the reference temperature is 298K

$$\text{Sensible heat in POC} = m_{CO2} \times \int Cp_{CO2}\, dT + m_{H2O} \times \int Cp_{H2O}\, dT + m_{N2} \times \int CpN_2\, dT$$

First we have to calculate the amount of POC. Combustion is complete with theoretical amount of air, POC consists of CO_2 H_2O and N_2 We can calculate the amount of each constituent of POC by the Stoichiometry of the reaction as illustrated in the lectures on combustion (Lecture 9-11). We can calculate heat carried by each constituent of POC at each temperature by using mxCpxdT. The calculated values are given in the table

POC	Sensible heat (kcal) at T =1000K	Sensible heat (kcal) T=1100K	Sensible heat (kcal) T = 1200k	Sensible heat (kcal)T = 1400K
CO_2	560	652	746	937
H_2O	209	222	235	261
N_2	1452	1675	1903	2346
Total	2161	2549	2884	3544
GAH	7339	6951	6616	5956

Increase in temperature from 1000K to 1400K decreases GAH by 19%. Decrease in GAH is followed by increase in fuel consumption in the same proportion

Exercise-IV Effect of excess air (self study)

Now consider that the above fuel is combusted with excess air to arrive at a furnace temperature of 1100K. Calculate GAH when a) excess air is 20% and b) when excess air is 50%

Calculations can be performed in a way similar to the above. The readers may do these calculations. The calculations show that increase in excess air decreases GAH from 7339 kcal at theoretical air to 6284 kcal at 20% excess air and 5561kcal at 50% excess air. This decrease in 14% at 20% and 24% at 50% excess air. Decrease in GAH will increase in fuel consumption

Calculations show further that preheating of theoretical amount of air to 500K will add 510 kcal sensible heat in air. As a result GAH will increase at all furnace temperatures

Exercise-V

The heat requirement of a process is $1.5\ x\ 10^3$ kW. The furnace is fired with coal which has 70% C. The NCV of coal is 27900 kJ/kg. The process is carried out at 1600K. Products of combustion analyse $76\%\ \mathrm{N_2}$ $7\ \%\ \mathrm{O_2}$ $5\%\ \mathrm{H_2O}$ and $12\ \%\mathrm{CO_2}$ Calculate fuel consumption

Solution :

Solution is presented in brief. The readers should calculate the values given

Since the POC temperature is not given. It is assumed that POC exit the furnace at the process temperature, i.e. 1600K.

Basis of calculation is 298K and 1 kg coal

By carbon balance, the amount of POC is 0.486 kg mol with the following composition

$\mathrm{CO_2} = 0.05832$ kg mol

$\mathrm{H_2O} = 0.0243$ kg mol

$\mathrm{O_2} = 0.034$ kg mol

$\mathrm{N_2} = 0.3694$ kg mol

Heat to POC can now be calculated by using Cp values. The calculated value of heat to POC is 22063kJ.

$\text{GAH/kg of coal} = 27900 - 22063 = 5837 \text{ kJ}$

$\text{Fuel consumption in kg/hr} = (1500 \times 3600)/5837 = 925 \text{kg/hr}$

Suppose the combustion air is preheated with the heat recovered from the POC in a heat exchanger which is having 50% relative efficiency. Calculate the fuel consumption

First we have to find amount of air. In this problem note that composition of coal is not completely given. Amount of air has to be calculated from the amount of POC:

$\text{Nitrogen in POC is nitrogen from air} = 0.3694 \text{ kg mole}$

$\text{Oxygen from air} = 0.0982 \text{ kg mole}$

$\text{Sensible heat in preheated air} = \text{relative efficiency x sensible heat in air at 1600K}$

$$= 0.5 \times (0.3694 \times 41620 + 0.0982 \times 43710)$$

$$= 9833 \text{ kJ}$$

$\text{GAH} = 27900 + 9833 - 22063 = 15670 \text{ kJ}$

One notes that GAH increases with the addition of sensible heat in air.

$\text{Fuel consumption} = 344 \text{ kg/hr}$

Fuel saving = 580 kg/hr; if the furnace operates for 20 hrs/day then coal saving is 11140 kg/day. Carbon saving is 8127 kg/day. This saving means that now less carbon will be discharged in the environment. This illustrates that preheating of air not only save fuel but also reduces carbon emission into the environment.

Now assume that the heat exchanger is not used. Coal is burned with a mixture of cold air ($25^{O}C$) and oxygen. Excess of oxygen (air + pure oxygen combined) over theoretical for combustion will be kept same as with preheater. Calculate the amount of oxygen required in kg/hr to obtain the same fuel consumption as obtained with the heat exchanger

Pre-heater adds 9833 kJ sensible heat into furnace. When pre-heater is not used, nitrogen of air must be reduced so that heat taken out by nitrogen equal to 9833 kJ

Let Y kg mol oxygen is required, this corresponds to 3.76Y of nitrogen

$\text{Thus } 3.76\text{Y x } 41620 = 9833$

$\text{Y} = 0.0628 \text{ kg mole which gives } 691 \text{ kg/hr of oxygen.}$

This problem illustrates the method of reduction of fuel by adopting technologies like preheating of air and oxygen enrichment of air. Both the technologies are in use to reduce the fuel consumption in industrial practice. Which technology suits has to be evaluated locally keeping in view the available resources and expertise.

What is energy flow diagram?

Energy flow diagram also known as Sankey diagram is a specific type of flow diagram in which the width of the arrows is proportional to the quantity of energy. Length of arrows has no bearings with the quantity of energy. These diagrams indicate the flow of energy in a process and help identifying the quality and quantity of energy. Quality of energy is indicated by the temperatures of inputs and outputs of energy. The input of energy begins from the left of the diagram. The outputs of energy are shown on the right side of the diagram as illustrated in the following figure:

Figure 39.1: Construction of an energy flow diagram

Exercise-VI

A furnace melts 305 tons of copper and raises its temperature to 1600K in 6 hrs. The furnace consumes 4.2 tons/hr oil. Fuel oil analyses 85% C, 12% H and 3% O and its net calorific value is 9446 kcal/kg. Combustion air is 20% excess than theoretically required. Heat loss from the furnace to the surrounding is 50% of the heat that is required to melt copper and raise its temperature to 1600K. Calculate the inputs and outputs of energy and show them on the energy diagram

First we have to do the material balance to find out the amounts of POC and then energy carried by POC by using the sensible heat values.

Sensible heat in POC is calculated to be 2.54×10^7 kcal/hr

Sensible heat in copper is calculated to be 0.95×10^7 kcal/hr

Heat losses are 50% of the sensible heat in copper = 0.48×10^7 kcal/hr

Heat balance :

Heat input	(kcal/hr)	% of total
Calorific value of fuel	3.97×10^7	100

Heat output	(kcal/hr)	% of total
Heat to POC	2.54×10^7	64
Heat to copper	0.95×10^7	24
Heat losses	0.48×10^7	12

The above values are shown in the figure

Figure 39.2: Energy flow diagram

Now consider the use of heat recovery device such as waste heat boiler. The POC enters the waste heat boiler and exit the boiler at 600K, Fifteen percent (15%) of the heat of POC is lost to the surrounding from the boiler. Show the flow of energy

Figure 39.3: Energy flow diagram showing the furnace and heat recovery system

Do yourself:

A heat balance for a continuous metallurgical process gives the following data:

Heat input	**% of total**
Combustion of fuel	100
Heat output	**% of total**
Process requirements	25
Sensible heat in flue gases	50
Heat loss	25

The installation of air preheater is being considered. It is estimated that the proposed preheater would recover one half of the sensible heat in the flue gases and would return to the furnace. Draw energy flow diagram in each of the following cases also

a) If the daily process requirements and daily heat loss are kept same, what percent saving in fuel could be achieved by the preheater installation? What would be the new heat balance (in percent) ?

b) If the daily fuel consumption and daily heat loss are kept same, what percent increase could be made in heat furnished to the process as a result of the preheater installation? What would be the new heat balance (in percent) ?

References:

Fine, H.Alan and G.H.Geiger: Handbook on Materials and Energy Balance Calculations in Metallurgical Processes