2. ENERGY PERFORMANCE ASSESSMENT OF FURNACES

2.1 Industrial Heating Furnaces

Furnace is by definition a device for heating materials and therefore a user of energy. Heating furnaces can be divided into batch-type (Job at stationary position) and continuous type (large volume of work output at regular intervals). The types of batch furnace include box, bogie, cover, etc. For mass production, continuous furnaces are used in general. The types of continuous furnaces include pusher-type furnace (Figure 2.1), walking hearth-type furnace, rotary hearth and walking beam-type furnace.(Figure 2.2)

The primary energy required for reheating / heat treatment (say annealing) furnaces are in the form of Furnace oil, LSHS, LDO or electricity
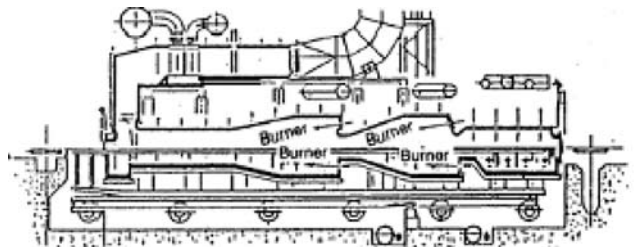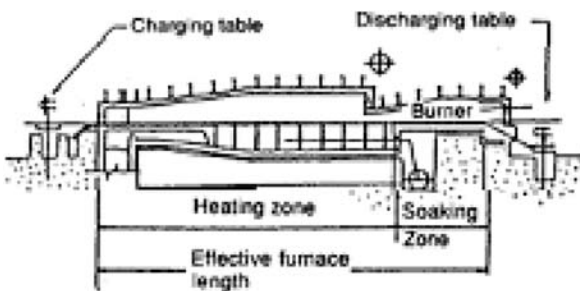

Figure 2.1:   Pusher-Type 3-Zone Reheating Furnace   Figure 2.2:   Walking Beam-Type Reheating Furnace

2.2 Purpose of the Performance Test

- To find out the efficiency of the furnace
- To find out the Specific energy consumption

The purpose of the performance test is to determine efficiency of the furnace and specific energy consumption for comparing with design values or best practice norms. There are many factors affecting furnace performance such as capacity utilization of furnaces, excess air ratio, final heating temperature etc. It is the key for assessing current level of performances and finding the scope for improvements and productivity.

Heat Balance of a Furnace

Heat balance helps us to numerically understand the present heat loss and efficiency and improve the furnace operation using these data. Thus, preparation of heat balance is a pre-requirement for assessing energy conservation potential.

2.3 Performance Terms and Definitions

1. Furnace Efficiency, η $\quad = \quad \dfrac{\text{Heat output}}{\text{Heat Input}} \times 100$

$\quad = \quad \dfrac{\text{Heat in stock (material)} \quad \text{(kCals)}}{\text{Heat in Fuel /electricity} \quad \text{(kCals)}} \times 100$

2. Specific Energy Consumption $\quad = \quad \dfrac{\text{Quantity of fuel or energy consumed}}{\text{Quantity of material processed.}}$

2.4 Reference Standards

In addition to conventional methods, Japanese Industrial Standard (JIS) GO702 "Method of heat balance for continuous furnaces for steel" is used for the purpose of establishing the heat losses and efficiency of reheating furnaces.

2.5 Furnace Efficiency Testing Method

The energy required to increase the temperature of a material is the product of the mass, the change in temperature and the specific heat. i.e. Energy = Mass x Specific Heat x rise in temperature. The specific heat of the material can be obtained from a reference manual and describes the amount of energy required by different materials to raise a unit of weight through one degree of temperature.

If the process requires a change in state, from solid to liquid, or liquid to gas, then an additional quantity of energy is required called the latent heat of fusion or latent heat of evaporation and this quantity of energy needs to be added to the total energy requirement. However in this section melting furnaces are not considered.

The total heat input is provided in the form of fuel or power. The desired output is the heat supplied for heating the material or process. Other heat outputs in the furnaces are undesirable heat losses.

The various losses that occur in the fuel fired furnace (Figure 2.3) are listed below.
1. Heat lost through exhaust gases either as sensible heat, latent heat or as incomplete combustion
2. Heat loss through furnace walls and hearth
3. Heat loss to the surroundings by radiation and convection from the outer surface of the walls
4. Heat loss through gases leaking through cracks, openings and doors.

Furnace Efficiency

The efficiency of a furnace is the ratio of useful output to heat input. The furnace efficiency can be determined by both direct and indirect method.

2.5.1 Direct Method Testing

The efficiency of the furnace can be computed by measuring the amount of fuel consumed per unit weight of material produced from the furnace.

Thermal efficiency of the furnace = $\dfrac{\text{Heat in the stock}}{\text{Heat in the fuel consumed}}$

The quantity of heat to be imparted (Q) to the stock can be found from the formula

$$Q = m \times C_p (t_2 - t_1)$$

Where

Q	=	Quantity of heat in kCal
m	=	Weight of the material in kg
C_p	=	Mean specific heat, kCal/kg°C
t_2	=	Final temperature desired, °C
t_1	=	Initial temperature of the charge before it enters the furnace, °C

2.5.2 Indirect Method Testing

Similar to the method of evaluating boiler efficiency by indirect method, furnace efficiency can also be calculated by indirect method. Furnace efficiency is calculated after subtracting sensible heat loss in flue gas, loss due to moisture in flue gas, heat loss due to openings in furnace, heat loss through furnace skin and other unaccounted losses from the input to the furnace.

In order to find out furnace efficiency using indirect method, various parameters that are required are hourly furnace oil consumption, material output, excess air quantity, temperature of flue gas, temperature of furnace at various zones, skin temperature and hot combustion air temperature. Efficiency is determined by subtracting all the heat losses from 100.

Measurement Parameters

The following measurements are to be made for doing the energy balance in oil fired reheating furnaces (e.g. Heating Furnace)

   i)   Weight of stock / Number of billets heated
   ii) Temperature of furnace walls, roof etc
   iii) Flue gas temperature
   iv) Flue gas analysis
   v)   Fuel Oil consumption

Instruments like infrared thermometer, fuel consumption monitor, surface thermocouple and other measuring devices are required to measure the above parameters. Reference manual should be referred for data like specific heat, humidity etc.

Example: Energy Efficiency by Indirect Method

An oil-fired reheating furnace has an operating temperature of around 1340°C. Average fuel consumption is 400 litres/hour. The flue gas exit temperature after air preheater is 750°C. Air is preheated from ambient temperature of 40°C to 190°C through an air pre-heater. The furnace has 460 mm thick wall (x) on the billet extraction outlet side, which is 1 m high (D) and 1 m wide. The other data are as given below. Find out the efficiency of the furnace by both indirect and direct method.

Flue gas temperature after air preheater = 750°C
Ambient temperature = 40°C
Preheated air temperature = 190°C
Specific gravity of oil = 0.92
Average fuel oil consumption = 400 Litres / hr
  = 400 x 0.92 =368 kg/hr
Calorific value of oil = 10000 kCal/kg
Average O_2 percentage in flue gas = 12%
Weight of stock = 6000 kg/hr
Specific heat of Billet = 0.12 kCal/kg/°C
Surface temperature of roof and side walls = 122 °C
Surface temperature other than heating and soaking zone = 85 °C

Solution

1. Sensible Heat Loss in Flue Gas:

Excess air $= \dfrac{O_2\%}{21-O_2\%} \times 100$

(Where O_2 is the % of oxygen in flue gas = 12%)
  = 12 x 100 / (21 - 12)
  = 133% excess air
Theoretical air required to burn 1 kg of oil = 14 kg (Typical value for all fuel oil)
Total air supplied = Theoretical air x (1 + excess air/100)
Total air supplied = 14 x 2.33 kg / kg of oil
  = 32.62 kg / kg of oil
Sensible heat loss = m x C_p x ΔT
    m = Weight of flue gas
  = Actual mass of air supplied / kg of fuel + mass of fuel (1kg)
  = 32.62 + 1.0 = 33.62 kg / kg of oil.
    C_p = Specific heat of flue gas
  = 0.24 kCal/kg/°C
    ΔT = Temperature difference

Heat loss = m x C_p x ΔT

$$= 33.62 \times 0.24 \times (750-40)$$
$$= 5729 \text{ kCal / kg of oil}$$

% Heat loss in flue gas $= \dfrac{5729 \times 100}{10000} = 57.29\%$

2. Loss Due to Evaporation of Moisture Present in Fuel

% Loss $= \dfrac{M\{584 + 0.45(T_{fg}-T_{amb})\}}{GCV \text{ of Fuel}} \times 100$

Where,

M	-	kg of Moisture in 1 kg of fuel oil (0.15 kg/kg of fuel oil)
T_{fg}	-	Flue Gas Temperature
T_{amb}	-	Ambient temperature
GCV	-	Gross Calorific Value of Fuel

% Loss $= \dfrac{0.15\{584 + 0.45(750-40)\}}{10000} \times 100$

$$= 1.36\%$$

3. Loss Due to Evaporation of Water Formed due to Hydrogen in Fuel

% Loss $= \dfrac{9 \times H_2\{584 + 0.45(T_{fg}-T_{amb})\}}{GCV \text{ of Fuel}} \times 100$

Where, H_2 – kg of H_2 in 1 kg of fuel oil (0.1123 kg/kg of fuel oil)

$$= \dfrac{9 \times 0.1123\{584 + 0.45(750-40)\}}{10000} \times 100$$

$$= 9.13\%$$

4. Heat Loss due to Openings:

If a furnace body has an opening on it, the heat in the furnace escapes to the outside as radiant heat. Heat loss due to openings can be calculated by computing black body radiation at furnace temperature, and multiplying these values with emissivity (usually 0.8 for furnace brick work), and the factor of radiation through openings. Factor for radiation through openings can be determined with the help of graph as shown in figure 2.4. The black body radiation losses can be directly computed from the curves as given in the figure 2.5 below.
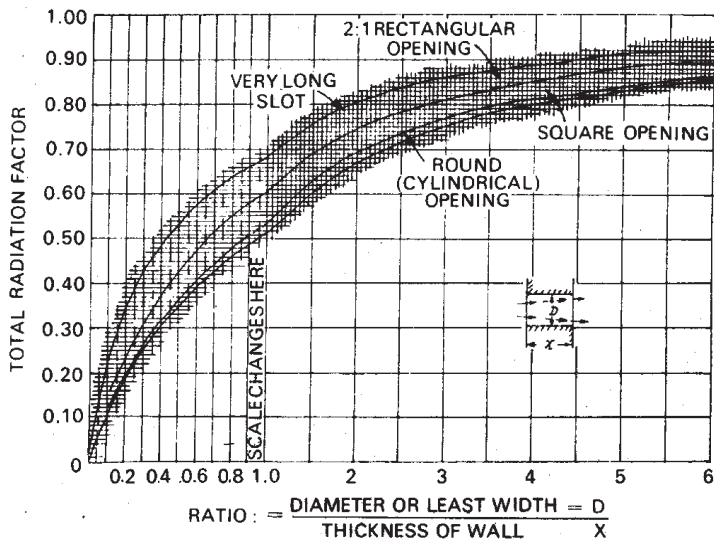
Figure 2.4   Factor for Determining the Equivalent of Heat Release from Openings to the Quality of Heat Release from Perfect Black Body
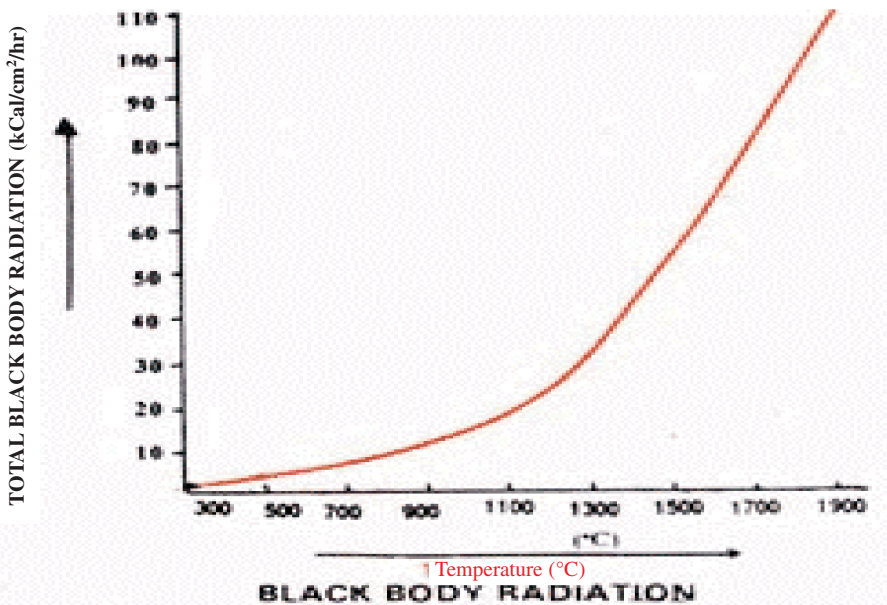
Figure 2.5   Graph for Determining Black Body Radiation at a Particular Temperature

The reheating furnace in example has 460mm thick wall (X) on the billet extraction outlet side, which is 1m high (D) and 1m wide. With furnace temperature of 1340°C, the quantity (Q) of radiation heat loss from the opening is calculated as follows:

The shape of the opening is square and D/X = 1/0.46 = 2.17
The factor of radiation (Refer Figure 2.4) = 0.71
Black body radiation corresponding to 1340°C = 36.00 kCal/cm^2/hr
(Refer Figure 2.5 On black body radiation)

Area of opening		=	100 cm x 100 cm
		=	10000 cm^2
Emissivity		=	0.8

Total heat loss = Black body radiation x area of opening x factor of radiation x emissivity

		=	36 x 10000 x 0.71 x 0.8
		=	204480 kCal/hr
Equivalent Oil loss		=	204480/10,000
		=	20.45 kg/hr
% of heat loss		=	20.45 /368 x 100
		=	5.56 %

5. Heat Loss through Skin:

Method 1: Radiation Heat Loss from Surface of Furnace

The quantity of heat loss from surface of furnace body is the sum of natural convection and thermal radiation. This quantity can be calculated from surface temperatures of furnace. The temperatures on furnace surface should be measured at as many points as possible, and their average should be used. If the number of measuring points is too small, the error becomes large.

The quantity (Q) of heat release from a reheating furnace is calculated with the following formula:

$$Q = a \ x \ (t_1 - t_2)^{5/4} + 4.88E\left[\left(\frac{t_1 + 273}{100}\right)^4 - \left(\frac{t_2 + 273}{100}\right)^4\right]$$

where

- Q : Quantity of heat release in kCal / W / m^2
- a : factor regarding direction of the surface of natural convection ceiling = 2.8, side walls = 2.2, hearth = 1.5
- t_1 : temperature of external wall surface of the furnace (°C)
- t_2 : temperature of air around the furnace (°C)
- E : emissivity of external wall surface of the furnace

The first term of the formula above represents the quantity of heat release by natural convection, and the second term represents the quantity of heat release by radiation.

Method 2 : Radiation Heat Loss from Surface of Furnace

The following Figure 2.6 shows the relation between the temperature of external wall surface and the quantity of heat release calculated with this formula.
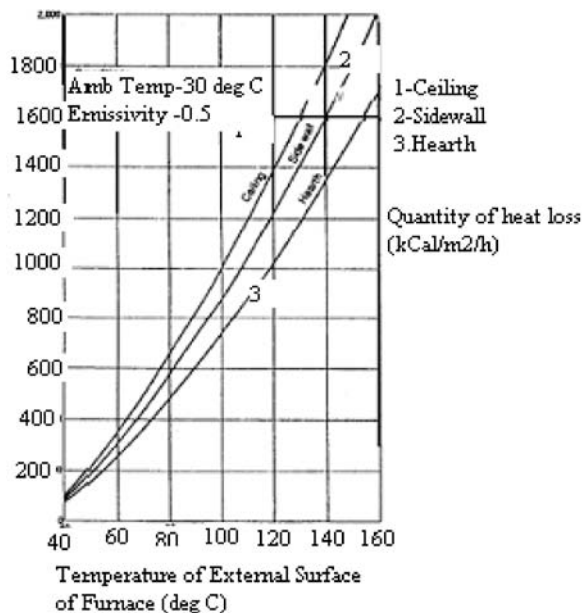
Figure 2.6 Quantity of Heat Release at Various Temperatures

From the Figure 2.6, the quantities of heat release from ceiling, sidewalls and hearth per unit area can be found.

5a). Heat loss through **roof and sidewalls:**

Total average surface temperature	=	**122°C**
Heat loss at 122 °C	=	1252 kCal / m^2 / hr
Total area of heating + soaking zone	=	70.18 m^2
Heat loss	=	1252 kCal / m^2 / hr x 70.18 m^2
	=	87865 kCal/hr
Equivalent oil loss (a)	=	8.78 kg / hr

5b). Total average surface temperature of
area other than heating and **soaking zone** = **85°C**

Heat loss at 85°C	=	740 kCal / m^2 / hr
Total area	=	12.6 m^2
Heat loss	=	740 kCal / m^2 / hr x 12.6 m^2
	=	9324 kCal/hr
Equivalent oil loss (b)	=	0.93 kg / hr
Total loss of fuel oil	=	a + b = 9.71 kg/hr
Total percentage loss	=	9.71 / 368
	=	2.64%

6. Unaccounted Loss

These losses comprise of heat storage loss, loss of furnace gases around charging door and opening, heat loss by incomplete combustion, loss of heat by conduction through hearth, loss due to formation of scales.

Furnace Efficiency (Direct Method)

Fuel input	=	400 litres / hr
	=	368 kg/hr
Heat input	=	368 x 10000 = 36,80,000 kCal
Heat output	=	m x C_p x ΔT
	=	6000 kg x 0.12 x (1340 – 40)
	=	936000 kCal
Efficiency	=	936000 x 100 / (368 x 10000)
	=	25.43 %
	=	25% (app)
Total Losses	=	75% (app)

Furnace Efficiency (Indirect Method)

1. Sensible heat loss in flue gas	=	57.29%
2. Loss due to evaporation of moisture in fuel	=	1.36 %
3. Loss due to evaporation of water formed from H_2 in fuel	=	9.13 %
4. Heat loss due to openings	=	5.56 %
5. Heat loss through skin	=	2.64%
Total losses	**=**	**75.98%**
Furnace Efficiency	**=**	**100 - 75.98**
	=	**24.02 %**
Specific Energy Consumption	=	<u>400 litre /hour</u> (fuel consumption)
		6 Tonnes/hour (Wt of stock)
	=	66.6 Litre of fuel /tonne of Material (stock)

2.5.4   Factors Affecting Furnace Performance

The important factors, which affect the efficiency, are listed below for critical analysis.

- Under loading due to poor hearth loading and improper production scheduling
- Improper Design
- Use of inefficient burner
- Insufficient draft/chimney
- Absence of Waste heat recovery
- Absence of Instruments/Controls
- Improper operation/Maintenance
- High stack loss
- Improper insulation /Refractories

2.6   Data Collection Format for Furnace Performance Assessment

The field-testing format for data collection and parameter measurements are shown below

Stock

Charged amount in furnace	Charging temperature	Discharging temperature	Discharge material
Tons/hr	°C	°C	kg/ton

Fuel Analysis

Fuel type	Consumption	Components of heavy oil						Gross calorific value	Temperature
		C	H_2	O_2	N_2	S	Water content		
	Kg/hr	%	%	%	%	%	%	kCal/kg	°C

Flue gas Analysis

Temperature	Composition of dry exhaust gas		
	CO_2	O_2	CO
°C	%	%	%

Cooling water

Amount of Water	Inlet temperature	Outlet temperature
kg/ton	°C	°C

Temperature of combustion air   =
Ambient air temperature   =

The Table 2.1 can be used to construct a heat balance for a typical heat treatment furnace

TABLE 2.1 HEAT BALANCE TABLE					
Heat Input			**Heat output**		
Item	**kCal/t**	**%**	**Item**	**kCal/t**	**%**
Combustion heat of fuel			Quantity of heat in steel		
			Sensible heat in flue gas		
			Moisture and hydrogen loss of fuel		
			Heat loss by Incomplete combustion (CO loss)		
			Heat loss in cooling water		
			Sensible heat of scale		
			Heat Loss Due To Openings		
			Radiation and Other unaccounted heat loss		
Total =		100%	Total =		100%

2.7 Useful Data

Radiation Heat Transfer

Heat transfer by radiation is proportional to the absolute temperature to the power 4. Consequently the radiation losses increase considerably as temperature increases.

°C1	°C2	K1 (°C1 +273)	K2 (°C2 +273)	$(K1/K2)^4$	Relative Radiation
700	20	973	293	122	1.0
900	20	1173	293	255	2.1
1100	20	1373	293	482	3.96
1300	20	1573	293	830	6.83
1500	20	1773	293	1340	11.02
1700	20	1973	293	2056	16.91

In practical terms this means the radiation losses from an open furnace door at 1500°C are 11 times greater than the same furnace at 700°C. A good incentive for the iron and steel melters is to keep the furnace lid closed at all times and maintaining a continuous feed of cold charge onto the molten bath.

Furnace Utilization Factor

Utilization has a critical effect on furnace efficiency and is a factor that is often ignored or under-estimated. If the furnace is at temperature then standby losses of a furnace occur whether or not a product is in the furnace.

Standby Losses

Energy is lost from the charge or its enclosure in the way of heat: (a) conduction, (b) convection; or/and (c) radiation

Furnace Draft Control

Furnace pressure control has a major effect on fuel fired furnace efficiency. Running a furnace at a slight positive pressure reduces air ingress and can increase the efficiency.

Theoretical Heat

Example of melting one tonne of steel from an ambient temperature of 20°C . Specific heat of steel = 0.186 Wh/kg/°C, latent heat for melting of steel = 40 Wh/kg/°C. Melting point of steel = 1600°C.

Theoretical Total heat = Sensible heat + Latent heat

Sensible Heat   =   1000 kg x 0.186 Wh /kg °C x (1600-20)°C = 294 kWh/T

Latent heat   =   40 Wh/ kg x 1000 kg   = 40 kWh/T

Total Heat   =   294 + 40 = 334 kWh/T

So the theoretical energy needed to melt one tonne of steel from 20°C = 334 kWh.
Actual Energy used to melt to 1600°C is 700 kWh

Efficiency = $\frac{334 \text{ kWh}}{700 \text{ kwh}}$ x 100 = 48%

Typical furnace efficiency for reheating and forging furnaces (As observed in few trials undertaken by an Energy Auditing Agency on such furnaces)

Pusher Type Billet Reheating Furnace (for rolling mills)

Furnace Capacity	Specific Fuel Consumption	Thermal Efficiency Achieved
Upto 6 T/hr	40-45 Ltrs/tonne	52%
7-8 T / hr	35-40 Ltrs/tonne	58.5%
10-12 T/hr	33-38 Ltrs/tonne	63%
15-20 T/hr	32-34 Ltrs/tonne	66.6%
20 T/hr & above	30-32 Ltrs/tonne	71%

Pusher type forging furnace

Furnace Capacity	Specific Fuel Consumption	Thermal Efficiency Achieved
500-600 kg/hr	80-90 Ltrs/tonne	26%
1.0 T/hr	70-75 Ltrs/tonne	30%
1.5-2.0 T/hr	65-70 Ltrs/tonne	32.5%
2.5-3.0 T/hr	55-60 Ltrs/tonne	38%

The above fuel consumption figures were valid when the furnaces were found to be operating continuously at their rated capacity.

Note: These are the trial figures and cannot be presumed as standards for the furnaces in question.

QUESTIONS	
1)	What is a heating Furnace and give two examples?
2)	Define furnace efficiency.
3)	How do you determine the furnace efficiency by direct method?
4)	How do you determine the furnace efficiency by Indirect method?
5)	Between efficiency and specific energy consumption, which is a better mean of comparing furnaces?
6)	List down the various heat losses taking place in oil-fired furnace.
7)	What are the major factors affecting the furnace performance?
8)	Apart from the furnace operating parameters, energy auditor needs certain data from reference book/manual for assessing furnace. Name few of them
9)	What will be the difference in approach for conducting efficiency testing of batch and continuous type furnace?
10)	How will you measure the temperature of the stock inside the furnace?

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