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Energy Audit Analysis Enhancing Energy Conservation in Foundry Industries by Minimizing Heat Losses in Induction Furnaces

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Abstract

Objectives: Implementing energy conservation in foundries, identification of energy losses from induction furnace in the form of conduction and radiation heat losses. **Method/Approach of Energy Audit:** The energy audit in this work consists of two phases and this piece of work focuses on the second phase which consists of identification and determination of conduction and radiation heat losses from induction furnace. A comparison for different values of furnace lining thickness shows conduction losses for each value of furnace lining thickness. The radiation losses are identified and the combined total losses are calculated. **Findings/Observations:** The conduction losses remain practically the same for all the operating temperatures of the furnace for a given thickness of furnace lining. The conduction losses are different for different values of furnace lining thickness. They increase as the lining thickness of furnace is increased. Radiation losses remain practically the same for all values of lining thickness for the entire operating temperature range. Radiation losses occur from the furnace opening and increases as the temperature of the furnace is increased. Thus, for the original thickness of 63 mm, the maximum and minimum heat efficiency is 93.1% at 1200°C and 86.27% at 1500°C respectively. The furnace does operate at an overall average heat efficiency of about 90% with a deviation of about ± 3% for a given value of thickness. **Application/Improvements:** A good energy management is the key towards energy conservation and it starts with an energy audit. The detailed energy audit analysis reveals good amount of energy saving in foundry and allied industries.

Keywords: Conduction and Radiation Heat Losses, Energy Audit, Energy Conservation, Furnace Efficiency, Heat Losses from Induction Furnace

1. Introduction

An energy audit is an evaluation of energy consumption in a home, business or any other premises such as college institutions, government institutions and offices, as well as industrial structures such as factories and manufacturing units. An energy audit is generally used to determine where energy can be saved, conserved or used more efficiently. With the world facing energy crisis and the lack of attention towards efficient energy use in industrial sector poses a great concern for the energy management teams in the industries. For this purpose, this work targeted the various opportunities and possibilities of finding solutions to the energy wastage and energy conservation in one of the foundry plant located at MIDC Amravati (Maharashtra, India). An energy audit is carried out within the foundry. The audit consisted of two main phases: a pre-audit phase that focused on identifying energy consumption points in the foundry unit such as various machines, water pumps, lighting etc and determining the energy wastage at these points.

2. Energy Audit Objectives

- The First objective was to acquire data by observations, analyzing the data and finding the energy consumption pattern of the facility.

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- The second objective was to calculate the wastage pattern based on the results of the first objective.
- The third objective was to find and implement solutions that are acceptable and feasible.
- The fourth objective was to acquire operational data of the induction furnace in the foundry and perform a thermal analysis.
- The final objective was to determine the energy consumption and energy loss characteristics of the furnace.

3. Methodology of Energy Audit

The method employed for energy audit and its analysis in this work has been divided in to two distinct phases viz. phase 1 and phase 2.

Phase-1: Employs the simple process of observing and identifying unnecessary energy consuming steps with an attempt to eliminate them. Various processes as well as equipments in the foundry shop floor were observed and the energy consuming points were pointed out and studied[1,3].

Phase–2: Employs the thermal analysis of induction furnace in the foundry. Of all the equipments and machineries that lie within the foundry, the furnace is the most energy consuming unit. The induction furnace as well as the cupola furnace requires a huge amount of energy to run continuously. Unlike cupola furnace which runs on fossil fuel and intermittently, the induction furnace on the other hand run on electricity continuously. Thus this energy audit was focused on the induction furnace to determine its energy consumption, energy losses in the furnace as well as the determination of its efficiency. This paper is dedicated to the work done in the phase 2 of the energy audit of the foundry.

3.1 Phase 2: Analysis of Heat Losses from Induction Furnace

The phase 2 of the energy audit is focused on the induction furnace. The induction furnace employs the principle of heat generation by electromagnetic induction. The electric energy is supplied to the furnace continuously to maintain the temperature of the furnace within the desired range. Typically, an induction furnace operates at temperatures in excess of 1200°C to up to 1500°C.

Despite supplying energy to the furnace constantly, energy is lost to the environment by the conduction and radiation processes. This energy audit is an effort to determine the losses by conduction and radiation combined and also to find the overall efficiency of the furnace.

4. Heat Losses in Conduction

Considering the furnace to be a cylinder, the general heat conduction equation[2] in cylindrical coordinates is given by:

$$\left[\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}.\frac{\partial T}{\partial r}+\frac{1}{r^2}.\frac{\partial^2 T}{\partial \phi^2}+\frac{\partial^2 T}{\partial z^2}\right]+\frac{q_g}{k}=\frac{1}{\alpha}.\frac{\partial T}{\partial t}$$

Assumptions:

- The heat transfer is assumed to be steady state.
- The heat flow is assumed to be unidirectional i.e. heat flow is along radial direction.
- Since it is a furnace, there is internal heat generation.
- It is assumed that all the energy supplied to the furnace is utilized to melt the metal within. That is no other energy losses occur other than the conduction and radiation losses.

$\therefore$ We have,

$$\left[\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}.\frac{\partial T}{\partial r}\right]+\frac{q_g}{k}=0$$

I.e. on solving, we have;

$$T_1-T_2=-\frac{1}{2}.\frac{q_g}{k}\left\{\frac{r_1^2}{2}-r_1^2\ln(r_1)\right\}-\left\{-\frac{1}{2}.\frac{q_g}{k}\left\{\frac{r_2^2}{2}-r_1^2\ln(r_2)\right\}\right\} \quad (3)$$

The above equation gives the temperature difference in the furnace lining's inner and outer surface with internal heat generation.

It is considered to be convenient to have a Heat transfer expression for a hollow cylinder (here it is the furnace) in the same form as that of a plane wall. Then the plane wall will have thickness $r_2 - r_1$, and its area will be equivalent to A_m as shown in Figure 1. A_m is such selected that the heat transfer is the same as that will be for the hollow cylinder for the same Thermal Potential. A_m is called the Logarithmic Area for the Hollow Cylinder[4,5].

We have;

$$A_m=\frac{A_o-A_i}{\text{h}\left(A_o-A_i\right)}$$

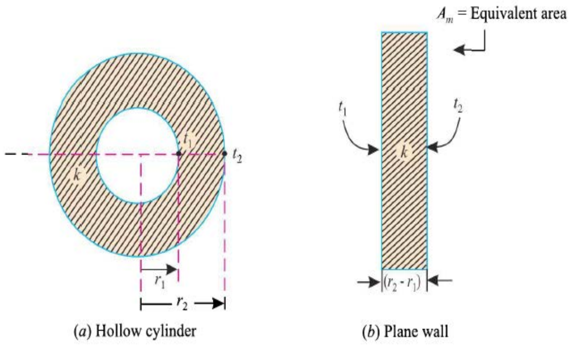

Figure 1. **(a)** Hollow cylinder **(b)** Plane wall with equivalent area A_m of the hollow cylinder.
Source of image: Er.R.K.Rajput, "Heat and Mass Transfer", Revised Edition, Published by: S.Chand and Co., New Delhi.

Where A_o and A_i are outer and inner surface areas of the hollow cylinder i.e. the furnace.

The heat transfer rate then will be expressed as:

$$Q = \frac{T_1 - T_2}{\left(\dfrac{r_2 - r_1}{k.A_m}\right)} \tag{4}$$

4.1 Heat Losses in Radiation

The contribution of radiation to heat transfer is very significant at high absolute temperatures that prevail in furnaces, combustion chambers, nuclear explosions and in space applications. Hot surfaces radiate energy to colder surfaces in their line of sight and the rate of heat transfer increases with the fourth power of the surface's absolute temperature. The biggest radiant energy loss in furnace operations is caused by doors remaining open longer than necessary, or doors left partially open to accommodate a load that is too large for the furnace.

The radiation energy per unit time from a black body is proportional to the fourth power of the absolute temperature and can be expressed with Stefan-Boltzmann Law as

$q = \sigma T^4 A$

Where

q = heat transfer per unit time (W)

σ = 5.6703 x10^{-8} (W/m^2K^4) - *The Stefan-Boltzmann Constant*

T = Absolute temperature in Kelvin (K)

A = Area of the emitting body (m^2)

For a real surface, the *Stefan-Boltzmann Law is given by* $q = E = \varepsilon.\sigma.A.T^4$

Where

ε = emissivity of the molten iron.

The average value of emissivity of molten pure iron is between 0.42 and 0.45 between the temperatures 1400 to 1700 degrees.

4.2 Calculations

4.2.1 Conduction Losses

The objective of the second phase is the determination of energy loss from the furnace by the combined phenomena of conduction as well as radiation.

We have,

$$T_1 - T_2 = \frac{1}{2}.\frac{q_g}{k}\left\{\frac{r_2^{\,2} - r_1^{\,2}}{2} - r_1^{\,2}\ln\left(\frac{r_2}{r_1}\right)\right\}$$

Now,

Volume of the furnace is

$$V = \pi r_1^{\,2}.h$$
$$V = \pi \times 0.21^2 \times .45$$
$$V = 0.062345mm^3$$

Therefore, Heat generated per unit volume of the furnace is Q_g.

$$Q_g = \frac{Q}{V}$$ — Q is the energy supplied to the furnace

$$Q_g = \frac{250\times10^3}{0.062345}$$
$$Q_g = 4009.944kW/m^3$$

Therefore, from the derived equation for temperatures, we can find the values of T_2 for different values of T_1. The values of T1 are the furnace internal temperature ranging from about 1200°C to 1500°C. the corresponding values are then charted in Table 1.

Now, we have

$$r_2 = 273mm$$
$$r_1 = 210mm$$
$$Q_g = 4009.944kW/m^3$$
$$k = 11W/m^\circ K$$

Now, Logarithmic Mean Area of plane wall equivalent to the surface area of the furnace cylindrical cavity is given by

So for r_2 = 273 mm

$$A_m = \frac{A_o - A_i}{\ln(A_o - A_i)}$$

$$A_m = \frac{2\pi \times h \times (r_2 - r_1)}{\ln(2\pi \times h \times (r_2 - r_1))}$$

$$A_m = \frac{2\pi \times 450 \times (273 - 210)}{\ln(2\pi \times 450 \times (273 - 210))}$$

$$A_m = 14733.2 mm^2$$

The obtained values of T_2 from T_1 above are then employed to find the heat transfer by conduction from the furnace. An important point to be noted here is that this heat transfer by conduction is equivalent to that which will occur in a plane wall. It is for this reason that an equivalent Logarithmic Mean Area is calculated for different values of r2 representing different sets of Furnace Lining Thickness. The obtained value of Q is then charted in Table 1 alongside the temperature values for a thickness of 63 mm (r_2 = 273 mm). Similarly, values of temperature and conduction loss are calculated for different values of lining thickness range of r_2 which is taken from 260 mm to 284 mm).

4.2.2 Radiation Losses

We have,

$$q = E = \varepsilon.\sigma.A.T^4$$

$$q = 0.42 \times 5.67 \times 10^{-8} \times \pi \times r_1^2 \times T^4$$

$$q =`0.42 \times 5.67 \times 10^{-8} \times \pi \times .21^2 \times T^4$$

$$q = 3.299 \times 10^{-9} \times T^4 Watts$$

The value of T varies from 1200°C to 1500°C thus giving different values of radiation losses. This is clearly charted in Table 3

4.3 For Conduction Losses

Thus from Table 1, we say that for a given thickness of lining of the furnace, the heat transfer is practically the same for the same thermal potential. This happens because equation 3 reveals same thermal potential for all the working temperature of the furnace. Also, we say that for as the thickness for the lining is increased, the heat transfer rate also increases[8,9].

Table 1. Temperature values and heat transfer by conduction for r2 = 273 mm

T_1		T_2		$Q = \frac{T_1 - T_2}{\left(\frac{r_2 - r_1}{k.A_m}\right)}$
°C	°K	°K	°C	Watts
1200	1473.15	808.91	535.76	1708.73
1225	1498.15	833.91	560.76	1708.73
1250	1523.15	858.91	585.76	1708.73
1275	1548.15	883.91	610.76	1708.73
1300	1573.15	908.91	635.76	1708.73
1325	1598.15	933.91	660.76	1708.73
1350	1623.15	958.91	685.76	1708.73
1375	1648.15	983.91	710.76	1708.73
1400	1673.15	1008.91	735.76	1708.73
1425	1698.15	1033.91	760.76	1708.73
1450	1723.15	1058.91	785.76	1708.73
1475	1748.15	1083.91	810.76	1708.73
1500	1773.15	1108.91	835.76	1708.73

Following tabulated data in Table 2 is thus obtained, clearly showing energy loss by conduction from the furnace for different values of lining thickness. The Table 2 is plotted in Figure 2.

Table 2. Total conduction losses for different values of lining thickness

Thickness	Heat Transfer Q
$r_2 - r_1$	$Q = \frac{T_1 - T_2}{\left(\frac{r_2 - r_1}{k.A_m}\right)}$
mm	*W*
50	1114.48
52	1198.5
54	1285.22
56	1374.6
58	1466.81
60	1561.6
62	1659
63	1708.73
64	1759
66	1861
68	1966.9
70	2075
72	2185
74	2297.87

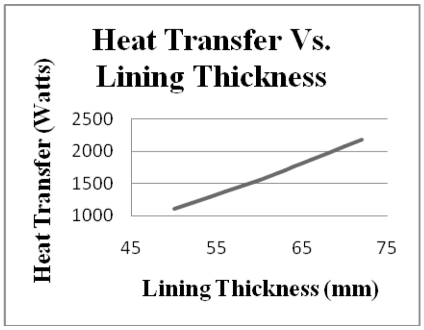

Figure 2. Relation between conduction losses as a function of furnace lining thickness.

4.4 For Radiation Losses

The values of radiation losses obtained for different values of temperatures within the furnace as shown in Table 3 is plotted on a graph as shown in Figure 3.

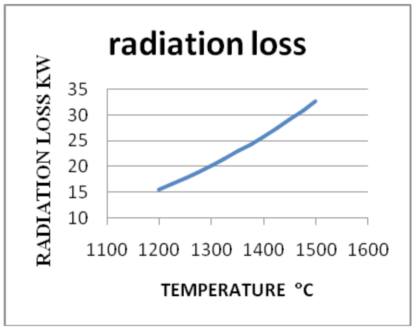

Figure 3. Radiation losses as a function of temperature.

Table 3. Radiation losses within operating temperature range of furnace

Temperature (T)		$q = 3.299\times10^{-9}\times T^4$
°K	°C	kW
1200	1473.15	15.537
1225	1498.15	16.618
1250	1523.15	17.756
1275	1548.15	18.951
1300	1573.15	20.205
1325	1598.15	21.52
1350	1623.15	22.899
1375	1648.15	24.342
1400	1673.15	25.8530
1425	1698.15	27.433
1450	1723.15	29.085
1475	1748.15	30.81
1500	1773.15	32.611

Now, for a given thickness of lining, the conduction losses remain the same throughout the temperature range. However, the radiation losses increase as the furnace temperature is increased. This can be shown in Table 4 where the given thickness is the original thickness of furnace lining i.e. 273 mm. Table 4 also charts the heat efficiency of the furnace for the 273 mm thickness of furnace lining.

For original thickness 63mm, i.e. for $r_2 = 273$ mm

Table 4. Total Loss and efficiency of furnace 63 mm thicknesses

Furnace temperature T_1		Conduction losses	Radiation losses	Total loss	Efficiency
°C	°K	$Q = \dfrac{T_1 - T_2}{\left(\dfrac{r_2 - r_1}{k.A_m}\right)}$ kW	$q = E = \varepsilon.\sigma.A.T^4$ kW	kW	$\eta = 1 - \dfrac{Q}{250kW}$
1200	1473.15	1.70873	15.537	17.245	93.102
1225	1498.15	1.70873	16.618	18.326	92.6696
1250	1523.15	1.70873	17.756	19.464	92.2144
1275	1548.15	1.70873	18.951	20.659	91.7364
1300	1573.15	1.70873	20.205	21.913	91.2348
1325	1598.15	1.70873	21.52	23.22873	90.70851
1350	1623.15	1.70873	22.899	24.60773	90.15691
1375	1648.15	1.70873	24.342	26.05073	89.57971
1400	1673.15	1.70873	25.8530	27.56173	88.97531
1425	1698.15	1.70873	27.433	29.14173	88.34331
1450	1723.15	1.70873	29.085	30.79373	87.68251
1475	1748.15	1.70873	30.81	32.51873	86.99251
1500	1773.15	1.70873	32.611	34.31973	86.27211

Table 4 shows maximum and minimum theoretical efficiencies of the furnace i.e. 93.1% and 86.2%. The values in Table 4 are plotted in graph shown in Figure 4 which shows relation between total losses and temperature for 63 mm thickness. Following the same pattern for all thicknesses we get the Table 5.

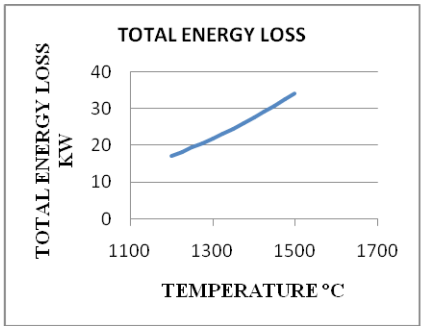

Figure 4. Relation between total losses and temperature for original lining thickness of 63 mm.

Table 5. Efficiency of furnace expressed as a function of different values of lining thickness

R_1	R_2	thickness	Efficiency η		Average
			Max.	Min.	efficiency
210	260	50	93.34	86.51	90.21
210	262	52	93.30	86.47	90.17
210	264	54	93.27	86.44	90.14
210	266	56	93.23	86.40	90.10
210	268	58	93.19	86.36	90.07
210	270	60	93.16	86.33	90.00
210	272	62	93.12	86.30	89.99
210	273	63	93.102	86.27	89.97
210	274	64	93.08	86.25	89.95
210	276	66	93.04	86.21	89.91
210	278	68	92.99	86.17	89.87
210	280	70	92.95	86.12	89.82
210	282	72	92.91	86.08	89.78
210	284	74	92.86	86.03	89.73

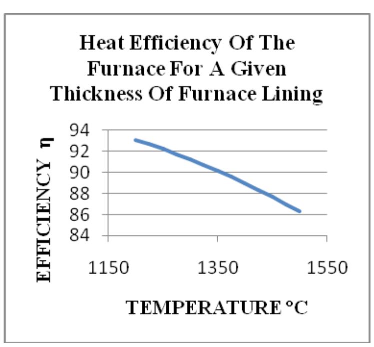

Figure 5. Heat efficiency of the furnace for original lining thickness of 63 mm expressed as a function of temperature.

5. Results

The phase 2 of the energy audit carried out in the foundry unit has following implications:

In the phase 2 of energy audit it is observed that the energy loss in the form of conduction remains practically the same for all the operating temperatures of the furnace for a given thickness of furnace lining. This happens due to the fact that the temperature equation derived gives an equal temperature gradient for all values of T_1. Heat transfer is always dependent on temperature gradient. Same gradients reveal equal heat transfers as conduction losses[6,7].

The conduction losses are different for different values of furnace lining thickness. It increases as the lining thickness of Furnace is increased. For original lining thickness of 63 mm, the conduction loss was about 1.7 kW. The heat loss gradually increases from about 1.11 kW for 50 mm thickness of furnace lining to about 2.23 kW for 74 mm thickness.

Radiation losses remain practically the same for all values of lining thickness for the entire operating temperature range from 1200°C to 1500°C. Radiation losses occur from the furnace opening and increases as the temperature of the furnace is increased. These losses increase from 15.5 kW at 1200°C to 32.6 kW at 1500°C. The radiation losses follow the Stefan-Boltzmann law and thus are a function of the fourth power of the absolute temperature of the furnace.

Although the conduction losses increase as the thickness of furnace lining is increased, however the overall efficiency of the furnace slightly decreases as the thickness is increased. This is due the presence of rising radiation losses from the furnace. Thus the furnace do operate at an overall average heat efficiency of about 90% with a deviation of about ± 3% for a given value of thickness. Thus, for the original thickness of 63 mm, the maximum and minimum heat efficiency is 93.1% at 1200°C and 86.27% at 1500°C respectively.

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