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Optimization of Wall Thickness for Minimum Heat Losses for Induction Furnace

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***Abstract* – This paper gives brief review of induction heating furnace as well as analysis of it. It is most important to reduce heat loss from induction furnace that can be moderate by new modern method and different heat losses in industrial heating furnaces are discussed. Wall thickness is geometrical parameter is used for optimization of furnace for reducing heat losses. Mathematical analysis as well as experimental analysis is done some traditional method or references. Finally by comparative results for three different materials such as alumina, magnesia and zirconia are discussed and effective results are come to be. Optimization of geometrical parameter such as wall thickness is give concluded results.**

Index Terms - Heat loss, Induction furnace, optimization etc.

I. INTRODUCTION

Induction heating processes have become increasingly used in these last years in industry. The main advantages of using these processes when compared to any other heating process (gas furnace.) are, among others, their fast heating rate, good reproducibility and low energy consumption. The Induction heating process basically consists in transmitting by electromagnetic means, energy from a coil through which an alternative current is circulating. Induced currents in the conductive part due to the well-known Foucault law then heat the work piece thanks to the Joule effect. Induction heating processes are mainly used either at low frequencies (around 50 Hz), usually in order to reach a temperature distribution as uniform as possible within the material before any forming process, or at much higher frequencies (104– 106 Hz) in order to heat very locally near the surface, usually for heat treatments.

The basic induction model is shown in the Fig.1. The extrusion industries use the furnace for heating of metal for their processes. The structure of furnace consists of inner space for metal melting, ramming mass for effective heat transfer and induction coil for the supply of heat. The design of induction furnace involves in the proper composition of the composite wall for the proper melting of metals. There are numerical calculations involved in the wall thickness but the industries fit the wall thickness mostly based on experience. Most induction heating processes are set up using engineering experience and a trial-and-error procedure in order to achieve the corresponding goal (grain size control, uniform prescribed temperature, hardness map, etc [1]. Induction heating process simulation, which couples electromagnetic and heat transfer equations, can be of great help for a more in depth understanding of occurring physical phenomena. So far, various numerical models have been developed coupling electromagnetism and heat transfer. Most models involve the well-known finite element approach or mixed finite element and boundary element approaches.

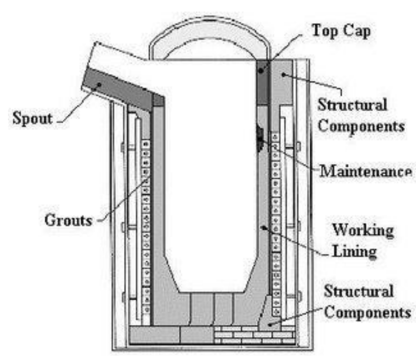


Fig.1. Furnace used in industries [1]

Hence proper optimization is needed in thickness. Increase in thickness plays an important role in effectiveness of the furnace. As the thickness increases the heat losses goes on decreasing up to a certain limit. Optimum thickness reducing heat loss in furnace with economical cost is needed [1]. Now a day's the increasing demand for electric power and the pursuit of its economical use, energy converters with higher and higher power have been developed and are being produced. In addition, the requirements of minimum electric power losses and environment protection have become extremely important, that is the minimization of the heat losses [1].

II. HEAT LOSSES IN INDUSTRIAL HEATING FURNACES

Mostly there are heat losses by conduction, convection and radiation, and hence the improvement in best refractory material and optimization in wall thickness of refractory material is needed. Induction furnaces are most commonly used for melting of metals. Especially silica ramming mass is used as refractory material to prevent losses.

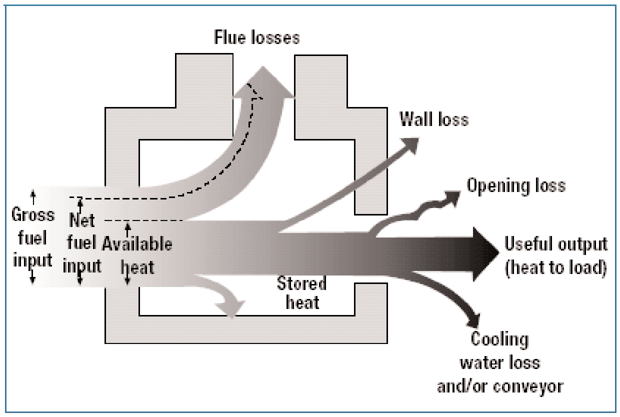


Fig.2. Modes of heat losses

These furnace losses include [2]:

1) Heat storage in the furnace structure
2) Losses from the furnace outside walls or structure
3) Heat transported out of the furnace by the load conveyors, fixtures, trays, etc.
4) Radiation losses from openings, hot exposed parts, etc.
5) Heat carried by the cold air infiltration into the furnace.
6) Heat carried by the excess air used in the burners.

A. Stored Heat Loss

First, the metal structure and insulation of the furnace must be heated so their interior surfaces are about the same temperature as the product they contain. This stored heat is held in the structure until the furnace shuts down, then it leaks out into the surrounding area [2]. The more frequently the furnace is cycled from cold to hot and back to cold again, the more frequently this stored heat must be replaced. Fuel is consumed with no useful output.

Wall losses:

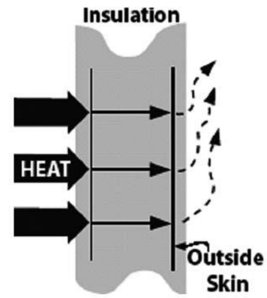


Fig.3. Wall Losses

Additional heat losses take place while the furnace is in production. Wall or transmission losses are caused by them conduction of heat through the walls, roof, and floor of the heating device, as shown in Fig.3. Once that heat reaches the outer skin of the furnace and radiates to the surrounding area or is carried away by air currents, it must be replaced by an equal amount taken from the combustion gases. This process continues as long as the furnace is at an elevated temperature.

B. Material Handling Losses

Many furnaces use equipment to convey the work into and out of the heating chamber, and this can also lead to heat losses. Conveyor belts or product hangers that enter the heating chamber cold and leave it at higher temperatures drain energy from the combustion gases [2]. In car bottom furnaces, the hot car structure gives off heat to the room each time it rolls out of the furnace to load or remove work. This lost energy must be replaced when the car is returned to the furnace.

C. Cooling Media Losses

Water or air cooling protects rolls, bearings, and doors in hot furnace environments, but at the cost of lost energy. These components and their cooling media (water, air, etc.) become the conduit for additional heat losses from the furnace. Maintaining an adequate flow of cooling media is essential, but it might be possible to insulate the furnace and load from some of these losses.

D. Radiation (Opening) Losses

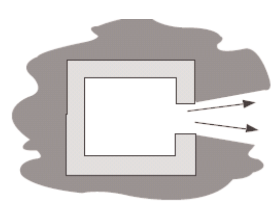


Fig.4. Radiation Loss

Furnaces and ovens operating at temperatures above 540°C might have significant radiation losses, as shown in Fig.4. Hot surfaces radiate energy to nearby colder surfaces, and the rate of heat transfer increases with the fourth power of the surface's absolute temperature. Anywhere or anytime there is an opening in the furnace enclosure, heat is lost by radiation, often at a rapid rate.

E. Waste-gas Losses

Waste-gas loss, also known as flue gas or stack loss, is made up of the heat that cannot be removed from the combustion gases inside the furnace. The reason is heat flows from the higher temperature source to the lower temperature heat receiver.

F. Air Infiltration

Excess air does not necessarily enter the furnace as part of the combustion air supply. It can also infiltrate from the surrounding room if there is a negative pressure in the furnace. Because of the draft effect of hot furnace stacks, negative pressures are fairly common, and cold air slips past leaky door seals, cracks and other openings in the furnace.

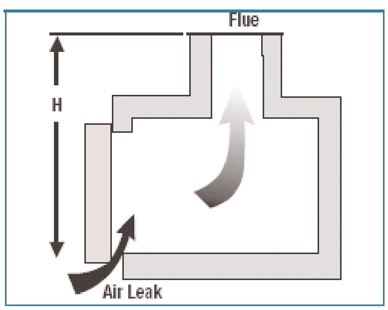


Fig.5. Air Infiltration from Furnace

Fig.5. illustrates air infiltration from outside the furnace. Every time the door is opened, considerable amount of heat is lost. Economy in fuel can be achieved if the total heat that can be passed on to the stock is as large as possible.

III. GENERAL FUEL ECONOMY MEASURES IN FURNACES

Typical energy efficiency measures for an industry with furnace are [3]:

1) Complete combustion with minimum excess air
2) Correct heat distribution
3) Operating at the desired temperature
4) Reducing heat losses from furnace openings
5) Maintaining correct amount of furnace draft
6) Optimum capacity utilization
7) Waste heat recovery from the flue gases
8) Minimum refractory losses
9) Use of Ceramic Coatings

A. Complete Combustion with Minimum Excess Air

The amount of heat lost in the flue gases (stack losses) depends upon amount of excess air. In the case of a furnace carrying away flue gases at 900°C, % heat lost is shown in table I.

TABLE I
HEAT LOSS IN FLUE GAS BASED ON EXCESS AIR LEVEL [3]

Excess Air	% of Heat in the full carried away by waste gases (Flue gas temp. 900^0C)
25	48
50	55
75	63
100	63

To obtain complete combustion of fuel with the minimum amount of air, it is necessary to control air infiltration, maintain pressure of combustion air, fuel quality and excess air monitoring higher excess air will reduce flame temperature, furnace temperature and heating rate. On the other hand, if the excess air is less, then unburnt components in flue gases will increase and would be carried away in the flue gases through stack. The optimization of combustion air is the most attractive and economical measure for energy conservation. The impact of this measure is higher when the temperature of furnace is high. Air ratio is the value that is given by dividing the actual air amount by the theoretical combustion air amount, and it represents the extent of excess of air.

B. Proper Heat Distribution

Furnace design should be such that in a given time, as much of the stock could be heated uniformly to a desired temperature with minimum fuel firing rate. Following care should be taken when using burners, for proper heat distribution [3]

1) The flame should not touch any solid object and should propagate clear of any solid object. Any obstruction will anatomize the fuel particles thus affecting combustion and create black smoke. If flame impinges on the stock, there would be increase in scale losses.

2) If the flames impinge on refractories, the incomplete combustion products can settle and react with the refractory constituents at high flame temperatures.

3) The flames of different burners in the furnace should stay clear of each other. If they intersect, inefficient combustion would occur. It is desirable to stagger the burners on the opposite sides.

4) The burner flame has a tendency to travel freely in the combustion space just above the material. In small furnaces, the axis of the burner is never placed parallel to the hearth but always at an upward angle. Flame should not hit the roof.

5) The larger burners produce a long flame, which may be difficult to contain within the furnace walls. More burners of

less capacity give better heat distribution in the furnace and also increase furnace life.
6) For small furnaces, it is desirable to have a long flame with golden yellow colour while firing furnace oil for uniform heating. The flame should not be too long that it enters the chimney or comes out through the furnace top or through doors. In such cases, major portion of additional fuel is carried away from the furnace.

C. Maintaining Optimum Operating Temperature of Furnace

It is important to operate the furnace at optimum temperature. Operating at too high temperatures than optimum causes heat loss, excessive oxidation, decarbonisation as well as over-stressing of the refractories. These controls are normally left to operator judgment, which is not desirable. To avoid human error, on/off controls should be provided.

D. Prevention of Heat Loss through Openings

Heat loss through openings consists of the heat loss by direct radiation through openings and the heat loss caused by combustion gas that leaks through openings. If the furnace pressure is slightly higher than outside air pressure (as in case of reheating furnace) during its operation, the combustion gas inside may blow off through openings and heat is lost with that. But damage is more, if outside air intrudes into the furnace, making temperature distribution uneven and oxidizing billets. This heat loss is about 1% of the total quantity of heat generated in the furnace, if furnace pressure is controlled properly [2].

E. Control of furnace draft

If negative pressures exist in the furnace, air infiltration is liable to occur through the cracks and openings thereby affecting air-fuel ratio control. Tests conducted on apparently airtight furnaces have shown air infiltration up to the extent of 40%. Neglecting furnaces pressure could mean problems of cold metal and non-uniform metal temperatures, which could affect subsequent operations like forging and rolling and result in increased fuel consumption. Some of the associated problems with ex filtration are leaping out of flames, overheating of the furnace refractories leading to reduced brick life, increased furnace maintenance, burning out of ducts and equipment's attached to the furnace, etc. In addition to the proper control on furnace pressure, it is important to keep the openings as small as possible and to seal them in order to prevent the release of high temperature gas and intrusion of outside air through openings such as the charging inlet, extracting outlet and peephole on furnace walls or the ceiling.

F. Optimum Capacity Utilization

One of the most vital factors affecting efficiency is loading. There is a particular loading at which the furnace will operate at maximum thermal efficiency. If the furnace is under loaded a smaller fraction of the available heat in the working chamber will be taken up by the load and therefore efficiency will be low. The best method of loading is generally obtained by trial-noting the weight of material put in at each charge, the time it takes to reach temperature and the amount of fuel used. Every endeavour should be made to load a furnace at the rate associated with optimum efficiency although it must be realized that limitations to achieving this are sometimes imposed by work availability or other factors beyond control.

G. Minimising Wall Losses

About 30–40% of the fuel input to the furnace generally goes to make up for heat losses in intermittent or continuous furnaces. The appropriate choice of refractory and insulation materials goes a long way in achieving fairly high fuel savings in industrial furnaces. The heat losses from furnace walls affect the fuel economy considerably. The extent of wall losses depends on [3].

• Emissivity of wall
• Thermal conductivity of refractories
• Wall thickness
• Whether furnace is operated continuously or intermittently

Heat losses can be reduced by increasing the wall thickness, or through the application of insulating bricks. Outside wall temperatures and heat losses of a composite wall of a certain thickness of firebrick and insulation brick are much lower, due to lesser conductivity of insulating brick as compared to a refractory brick of similar thickness. In the actual operation in most of the small furnaces the operating periods alternate with the idle periods. During the off period, the heat stored in the refractories during the on period is gradually dissipated, mainly through radiation and convection from the cold face.

H. Use of Ceramic Coatings

Ceramic coatings in furnace chamber promote rapid and efficient transfer of heat, uniform heating and extended life of refractories. The emissivity's of conventional refractories decreases with increase in temperature whereas for ceramic coatings it increases. This outstanding property has been exploited for use in hot face insulation. Ceramic coatings are high emissivity coatings which when applied has a long life at temperatures up to 1350°C. The coatings fall into two general categories-those used for coating metal substrates, and those used for coating refractory substrates. The coatings are non-toxic, non-flammable and water based. Applied at room temperatures, they are sprayed and air dried in less than five minutes. The coatings allow the substrate to maintain its designed metallurgical properties and mechanical strength. Installation is quick and can be completed during shut down.

Energy savings of the order of 8–20% have been reported depending on the type of furnace and operating conditions.

IV. STUDY OF EXISTING FURNACE

Capacity : 180Kg
Furnace dimension: 10''*21''*42''
Lining thickness : 2"
Lining material : Silica
Body material : Aluminium

A. Analytical study

Furnace has generally heat losses by conduction, convection and radiation. Heat loss can be calculated from several methods, but apart from those methods we must justify proper method for more accurate results. Here it is determined that heat conduction through composite wall for calculations of heat losses and temperature distribution from furnace is proper method and it gives us accurate results. Sometimes assumptions can be required for calculations of heat losses. Mathematical calculation needs temperature at inner and outer wall of the furnace, thermal conductivity of each material.
Temp. Of inner wall: 1400^0c
Temp. Of outer wall: 40^0c

TABLE II.
MATERIAL PROPERTIES OF THE DIFFERENT RAMMING MASS [3]

Ramming mass	Thermal conductivity(w/m^{0}k)
Alumina	16
Magnesia	15
Zirconia	7.5

B. Heat Loss Calculation

Heat loss can be calculated by considering the furnace as a composite wall. Consider the transmission of heat through a composite wall consisting of number of slots [4].
Let,

L_A, L_B = Thickness of slabs A & B resp.
K_A, K_B = Thermal conductivity of the slabs A & B resp.
T_1 = Temp of inner wall
T_4 = Temp of outer wall

Since the quantity of heat transmitted per unit time through each slab is same, we have

$$Q = \frac{K_A * A(t_1 - t_2)}{L_A} = \frac{K_B * A(t_1 - t_2)}{L_B} = \frac{K_A * A(t_1 - t_2)}{L_C}$$

Assuming that there is perfect contact between the layers and no temperature drop across the interface between the materials. If the composite wall consists of n slabs, then

$$Q = \frac{(t_1 - t_{(n+1)})}{\sum_1^n \frac{L}{kA}}$$

1. Alumina:

$$Q = \frac{1400 - 40}{\left(\frac{50}{16} + \frac{2}{175}\right)}$$

$= 4.33e^5$ W or 1558.8 Kwh

2. Magnesia:

$$Q = \frac{1400 - 40}{\left(\frac{50}{15} + \frac{2}{175}\right)}$$

$= 4.06e^5$ W or 1461.6 Kwh

3. Zirconia:

$$Q = \frac{1400 - 40}{\left(\frac{50}{7.5} + \frac{2}{175}\right)}$$

$= 2.03e^5$ W or 730.8 Kwh

TABLE III
OBSERVATIONS OF HEAT LOSS IN FURNACE WALL

Thickness in mm	Heat loss in kwh		
	Alumina	Magnesia	Zirconia
50	1566	1469	734
55	1422	1332	666
60	1303	1224	612
65	1202	1127	562
70	1116	1048	522
75	1044	979	490
80	979	918	457
85	922	864	432
90	868	814	407
95	824	770	385
100	781	734	367
105	745	698	349
110	724	680	338
115	695	652	324
120	666	623	310
125	637	598	299
Thickness in mm	Heat loss in kwh		
	Alumina	Magnesia	Zirconia
130	612	576	288
140	569	533	288
150	565	529	288
160	563	528	-------
170	562	528	-------

180	562	-------	-------

Verification with the analytical results, It is needed to verify analytical and software results.

TABLE IV
ANALYTICAL AND SOFTWARE RESULT VERIFICATION

Material(50mm)	Heat flow Kwh	
	Software	Analytical
Alumina	$4.35e^5$	$4.33e^5$
Magnesia	$4.08e^5$	$4.06e^5$
Zirconia	$2.04e^5$	$2.03e^5$

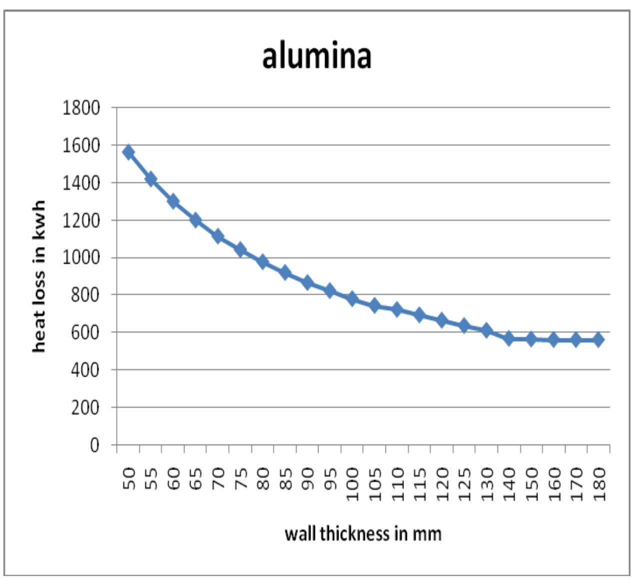
The verified values of calculated results by using software are closer to actual measured values. Optimization of wall thickness

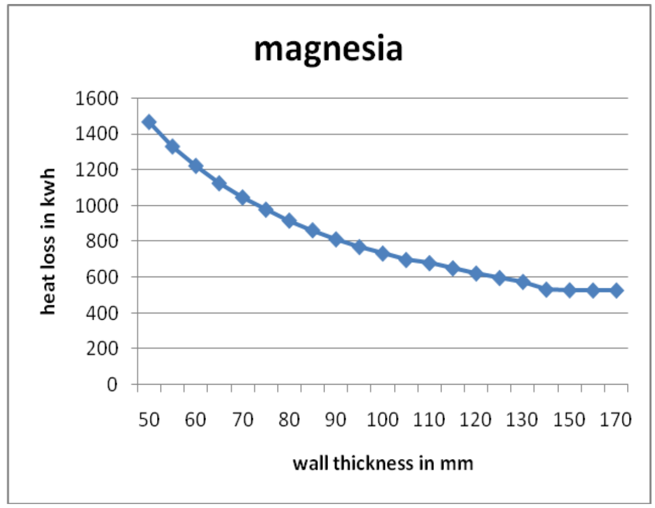
TABLE V
OPTIMUM WALL THICKNESS

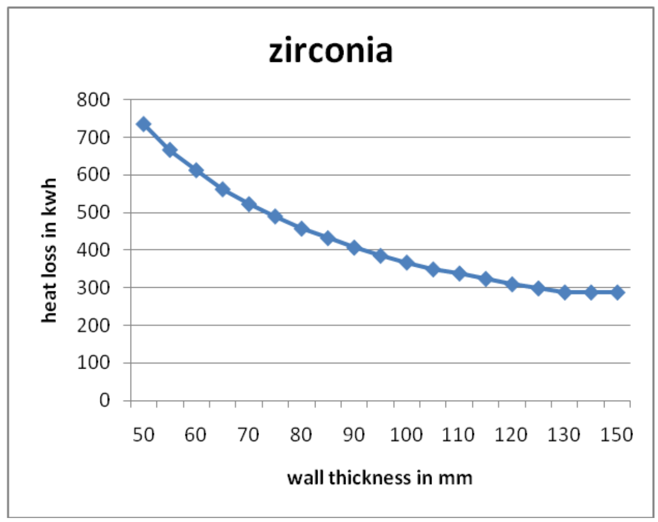
Material	Wall thickness in mm	Heat loss in kwh
Alumina	170	562
Magnesia	160	528
Zirconia	130	288

V. RESULTS AND DISCUSSIONS

Following graph shows the effect of wall thickness on heat losses. Effect of increasing in thickness of refractory material is reduced heat losses are shown for different ramming masses.

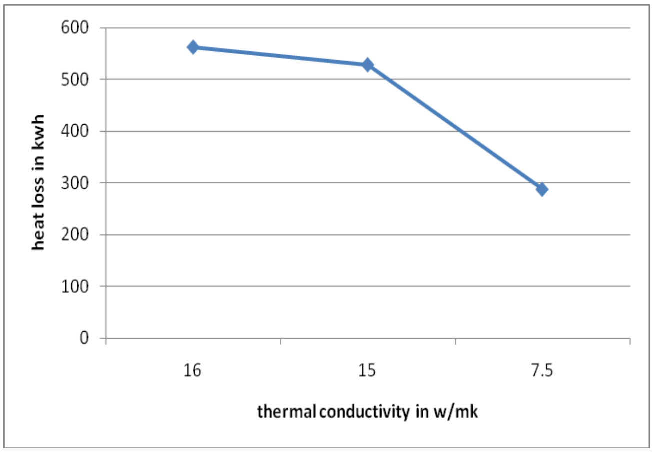






Graph 1. Heat loss profile for optimum thickness of ramming mass for alumina, magnesia and zirconia.

Following graph shows the effect of optimum material properties on the heat losses. Increasing thermal conductivity effects on temperature and losses from furnace, so it must be as lower as possible.



Graph 2. Heat loss profile for optimum properties of ramming mass

VI. CONCLUSION

The optimization plays an important role to reduce losses and provides a good temperature distribution profile. From above results it is concluded that reduction of 48% losses from properties optimization and 64 % by geometrical optimization. Finally optimum geometry and properties of ramming mass can reduce total 60% losses with optimum thickness and properties of material of induction furnace.

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