Numerical Analysis and Investigation of Temperature Distribution in a Furnace during Steady State Condition Using Yttria

J Govardhan, J Narsaiah

Abstract: **This paper deals with an integrated numerical and experimental analysis work investigating into the effect of changes in temperature in a crucible furnace built for metal melting process. Furnace operating conditions employing the application of Yttria in place of brick used in furnace was carried out to study temperature variations inside the crucible furnace.**

The experimental values of temperature during conventional combustion carried out in a crucible furnace with brick lining were taken as boundary conditions as inputs and studied the temperature changes by embedding brick with Yttria at equal intervals of time schedule. The results indicate that by embedding the brick by Yttria resulted inenhanced temperatures at different zones inside the furnace and significance impact on thermal radiation and the heat transfer rate in the furnace.

Key words: Yttria, brick, crucible furnace, steady state, numerical simulation.

I. INTRODUCTION

In the past research has been conducted on radiation and convective heat transfer modes and developed many methods of heat transfer enhancements from simple to complex. Analysis of forced convection is an important heat transfer mode in the heating industries such as furnaces, boilers, glass melting and IC engines. Therefore the design of the equipment for enhanced heat transfer is an important criterion.

The objective of the work is to study the temperatures at different points in a furnace and analysis of its effects on convective heat transfer by using empirical and numerical methods. The experimental data obtained from brick lining were used to analyze the Yttria.

The study of temperature distribution and changes of induction heating furnace can offer theoretical support to choose and determine a reasonable heating system in actual production by using numerical simulation. Modeling was carried out on the furnace for temperature distribution in the furnace during steady state combustion [1].

Also the study analysis of natural convection phenomena in enclosures has become one of the major topics of interest in research due to its applications involved in various engineering processes [2].

Considering the Thermal radiation in gaseous media has become an important mode of heat transfer in high temperature chambers, such as industrial furnaces and boilers, even under non-soot conditions. Growing concern with high temperature processes has emphasized the need for an evaluation of the effect of radiative heat transfer. For example, thermal radiation affects significantly the structure and extinction characteristics of a methane air flame due to the radiative cooling mechanism [3].

Energy conservation and efficiency have always been the quest of engineers concerned with internal combustion engines as well if the heat rejected could be reduced, then the thermal efficiency would be improved [4].

According to O.O.Oluwole et.al, heat flow patterns in two salt bath furnaces were studied in this work using finite element (FE) analysis. The implications of the heat flow on long term stability of furnace performance were evaluated. One design had purely silica brick backup after the embedded heating element with asbestos and glass wool fiber insulation just before the outer steel shell [5].

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 [6].

As per O. Delabroyet.al, in addition with productivity increase and bottlenecking, specific issues may exist which are also solved using ALROLL™. Energy saving is one of these issues, especially for furnaces with no or with a low efficiency fumes energy recovering system [7].

The effect of changes in furnace operating conditions were investigated by ShuaibuNdache Mohammed. The operating conditions considered were the air preheats convection, fuel flow rates, excess air and air infiltration. For each of these conditions, the mean gas temperature, furnace output and thermal efficiencies were evaluated. The evaluation of thermal performance of fuel fired furnace is dependent on an accurate calculation of radiant exchange between the combustion products, wall and stock within the heating chamber [8].

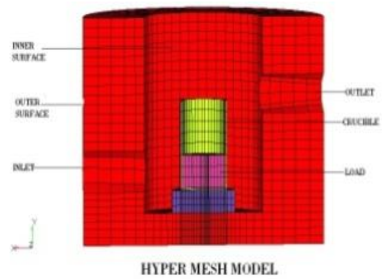
II. NUMERICAL SIMULATION (TOOLS USED FOR NUMERICAL SIMULATION)

The furnace model was developed by Pro E (Wildfire 4) software, Hyper works – 10.0 software in meshing the model and ANSYS-12 software for analysis. By Hyper mesh solid mesh is done by which a model developed in Pro-E is meshed by 17011 elements and 7468 nodes with an element size of 10.In Hyper mesh temperature properties were given to the model meshed.

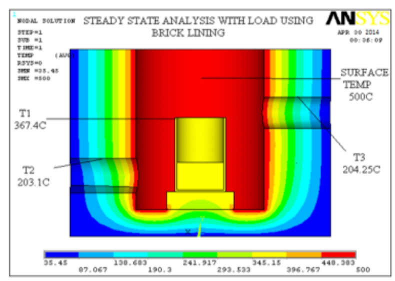
Static analysis applied in this model which calculates the effects of static loads on the structure while ignoring the inertia and damping effects such as those caused by time varying loads but can accomplish steady inertia loads static equivalent loads.

Prediction of thermal radiation is an impressive heat transfer mode in the furnace, and combustion chamber and therefore the design of these for many relevant heat transfer industries is paramount. In the past many research efforts in radiative heat transfer field were applied and developed many methods and models from simple to complex. The objective of this work is to study the temperature changes at different points in a furnace and its effect on the radiative heat transfer by empirical and numerical methods using experimental data obtained earlier for brick lining.

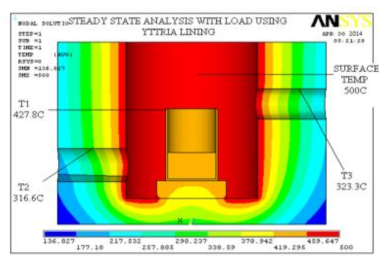
Furnace configuration



Steady state brick

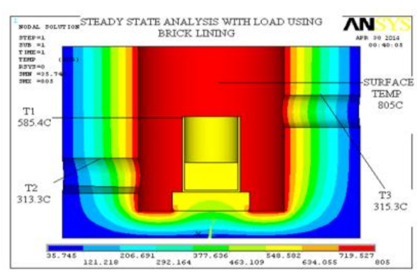


Steady state yttria

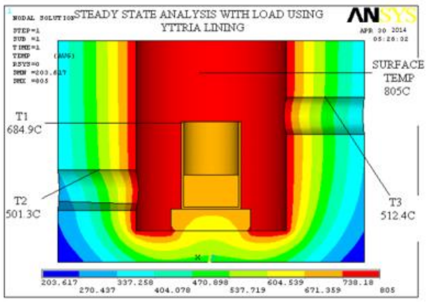


(a) Temperature contour (at 10 minute)

Steady state - Brick

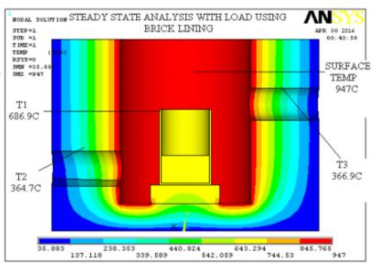


Steady state - Yttria

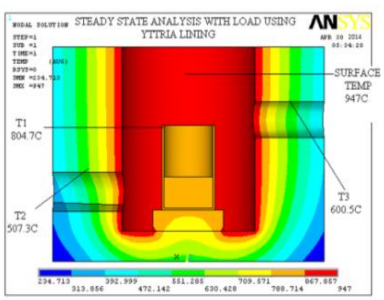


(b) Temperature contour (at 20 minute)

Steady state brick

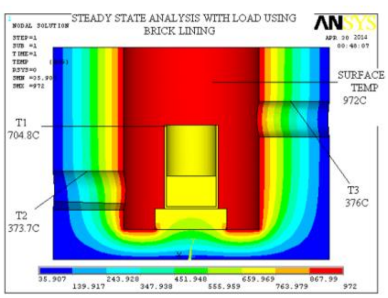


Steady state yttria

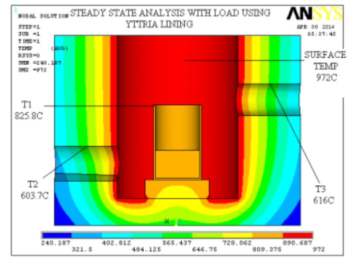


(c) Temperature contour (at 30 minute)

Steady state brick

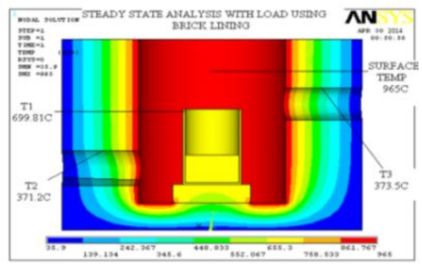


Steady state yttria

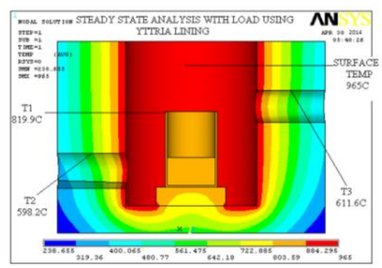


(d) Temperature contour (at 40 minute)

Steady state brick



Steady state yttria



(e) Temperature contour (at 50 minute)

Boundary conditions

Combustion air inlet temperature: Ambient
Combustion air inlet velocity: 58 m/s (constant)
Fuel Used: Diesel ($C_{10}H_{22}$)
Fuel inlet temperature: Ambient
Fuel inlet velocity: 13 m/s
Time-step: 10 minute
Commercial CFD package: ANSYS FLUENT-12

III. FLOW OVER CYLINDERS

The case of heating of a crucible furnace by forced convection by flame flowing across it.

In order to calculate the Reynolds number Re, the characteristic length taken in case of cylinder and sphere as well, is its external diameter D.As usual, Re= $\frac{UD}{\nu}$Where U= Uniform velocity of flow as it approaches the cylinder (sphere).In case of flow across cylinders (or spheres)the critical Reynolds number is Re =2x10^5.Up to this value laminar boundary layer exists and beyond this boundary layer becomes turbulent.

IV EMPIRICAL CORRELATION USED FOR TURBULENT FLOW (CROSS FLOW) OVER CYLINDER

The following empirical correlation is widely used for turbulent flow over cylinders

$$\overline{Nu} = \frac{hD}{k} = C\,(Re)^n\,(\mathrm{Pr})^{0.33} \quad (1)$$

Where C and n are constants and have the values as given in the table below

S.No	Re	C	n
1	0.4 to 4	0.989	0.33
2	4 to 40	0.911	0.385
3	40 to 4x10^3	0.683	0.466
4	4x10^{3}to 4x10^4	0.193	0.618
5	4x10^4 to 5x10^5	0.026	0.805

Churchill and Bernstein have suggested the following comprehension empirical correlation which covers the entire range of Re and wide range of Pr

$$\overline{Nu} = 0.3 + \frac{0.62(Re)^{0.5}\,(\mathrm{Pr})^{0.33}}{\left[1+\left(\frac{0.4}{Pr}\right)^{2/3}\right]^{0.25}}\left[1 + \left(\frac{Re}{28200}\right)^{5/8}\right]^{0.8} \quad (2)$$

Above equation is valid for 100 <Re<10^7, and Re.Pr>0.2 and correlates very well all available data

The following equation may be used in the mid-range of Reynolds members,

i:e 20,000 < Re <400,000:

$$\overline{Nu} = \frac{hD}{k} = \overline{Nu} = 0.3 + \frac{0.62(Re)^{0.5}\,(\mathrm{Pr})^{0.33}}{\left[1+\left(\frac{0.4}{Pr}\right)^{2/3}\right]^{0.25}}\left[1 + \left(\frac{Re}{28200}\right)^{5/8}\right]^{0.8} \quad (3)$$

For 20,000 < Re <400,000, and Re.Pr> 0.2

The following relation is recommended by Nakai and Okazaki for Pe (=Re.Pr)<0.2

$$\overline{Nu} = [0.8237 - \ln(Pe)^{0.5}]^{-1} \quad (4)$$

Allproperties, for all the above Equations are evaluated at the ‘film temperature”

(i:e $t_f = \frac{t_s + t_\infty}{2}$ where t_f, t_s, t_∞ are film, surface, free surface temperature (in ^{o}C) respectively.

For liquid metals Ishiguro et.al recommended following relation for heat transfer from a single cylinder in cross flow.

$$\overline{Nu} = 1.125(Re.Pr)^{0.413} \, for \; 1 < Re.Pr < 100 \quad (5)$$

For gases the following relation is widely used for circular cylinder in cross flow

$$\overline{Nu} = C.(Re)^n\,.(\mathrm{Pr})^{1/3} \quad (6)$$

Where values of C and n are given in the table

All the fluid properties are taken at film temperature.

IV. RESULTS AND DISCUSSION

VARIATION IN TEMPERATURE WITH TIME FOR STEADY STATE CONDITIONS

Experimental investigations were carried out on the brick and the boundary conditions of brick for steady state are used to make analysis on yttria. The influence of combustion time on the temperature at 20 kg load is tabulated. Identified temperature points on T_1, T_2, T_3, for brick and yttria. T_1 defines temperature at surface of crucible, T_2 at fuel inlet and T_3 at the exit of the flue gases from furnace.

There found to be improvement in the temperature of yttria in comparison to brick. This may be due to the properties of yttria such as high thermal conductivity, low thermal resistance and chemical inertness contributed for the enhanced temperature .

Observations have been made from Table 1 and Figure 1 whch represent the relation between time and temperature.

As the time elapsed it was noticed that the sudden rise in temperature for both at 10 and 20 minutes of time intervals was gradual for the next phase of time intervals. This was due to the large thermal gradients prevailed between the furnace enclosure and the crucible along with the metal. However there found to be noticeable difference in the temperature of brick and yttria.

Table 1. Comparisons of T_1 BetweenBrick and Yttria.

TIME (Min)	Brick T_1°C	Yttria T_1°C	% enhancement
10	367	427	14.11
20	585	684	14.52
30	686	804	14.63
40	699	819	14.6
50	704	825	14.6

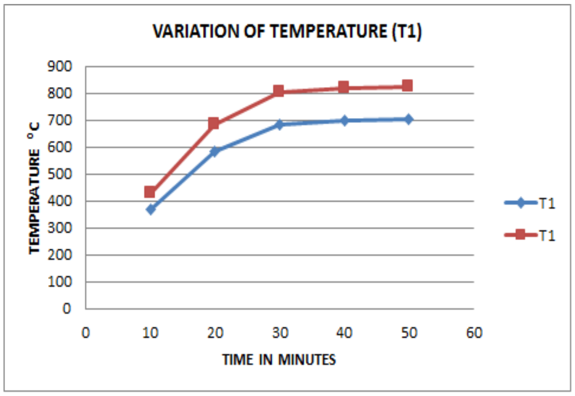


Fig. 1. T_1 Brick and Yttria results

It can be seen from the Table 2 and Fig 2 that the rise in temperature was large up to 20 minutes of time interval for both brick and yttria. But there was small increment of rise in temperature for yttria in comparison to brick. This may be due to large amount of absorption of heat by the load in the crucible furnace due to the temperature gradient between the load and furnace temperature at point 2. After some time gap again there was rise in temperature in both yttria and brick but rise in temperature is significant in yttria.

Table 2 – Comparisons of T_2 between Brick and Yttria.

Time (min)	Brick T_2°C	Yttria T_2°C	% enhancement
10	203	316	35.84
20	313	501	37.5
30	364	507	28.1
40	371	598	37.9
50	373	603	38.09

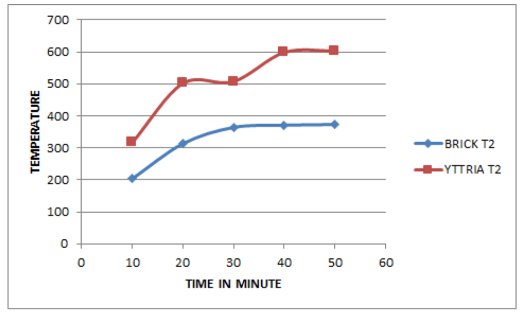


Fig. 2. T_2 Brick and Yttria results

From the available data from the Table 3 and Fig 3 the analysis can be made that the temperatures available for both yttria and brick during different intervals of time are more or less the same for Table 2 and 3 but for Table 1 The out going flue gases from the furnace would interact with heat transferred by the walls of the furnace due to radiation and convection of molecules of heat at the interface of point T_2 and T_3 there by the incremental hike in the temperature T_3.

Table 3 – Comparisons of T_3 between Brick and Yttria.

Time (Min)	Brick T_3°C	Yttria T_3°C	% enhancement
10	204	323	36.83
20	315	512	38.46
30	366	600	38.9
40	373	611	38.9
50	376	616	38.96

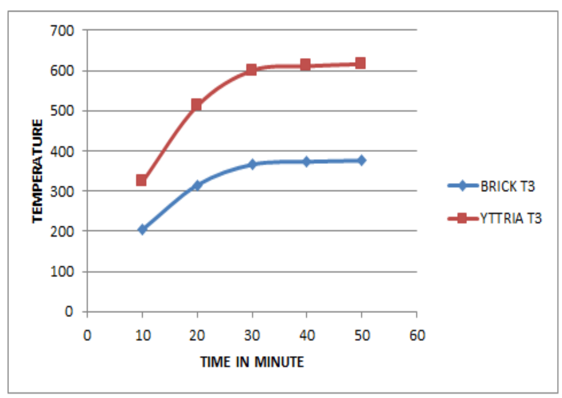


Fig. 3. T_3Brick and Yttria results

Table 4 – Percentage of enhancementin T_1, T_2, T_3

TIME (min)	T_1	T_2	T_3
10	14.11	35.84	36.83
20	14.52	37.5	38.46
30	14.63	28.1	38.9
40	14.6	37.9	39.9
50	14.6	38.09	38.96

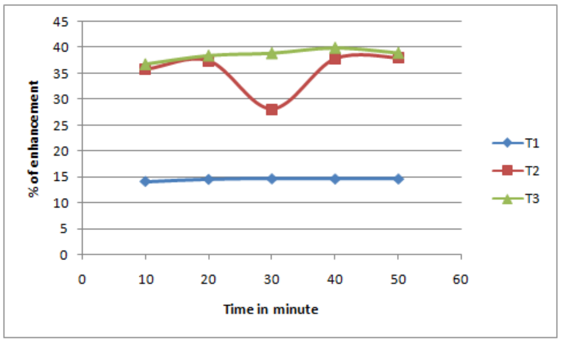


Fig. 4. Percentage of enhancement in T_1, T_2, T_3

From the Table 4 and Fig 4the percentage of enhancement in T_1 with respect to the time was found marginal but high for yttria when compared to brick. It can be said that the absorption of thermal energy from the hot gases by the load is optimum. The heat energy transfer from the turbulent gases to the load was significant because of large thermal gradients prevailing between hot gases and load in the furnace. As the hot gases swirls around the crucible in furnace the impingement of thermal energy to the load was pertinent.

The percentage of enhancement on T_2 and T_3, was high except at the time interval of 30 minutes for T_2. This was perhaps due to the boundary layer conditions prevailing at the designated points of T_2, and T_3, during other time intervals.

V. CONCLUSION

The objective of the paper was to study the temperature distribution inside a furnace using brick and yttria during study state conditions. Since the enhancement in temperature using yttria was found to be fairly good there by useful for heat transfer industries to replacebrick with Yttria.

- The furnace temperature increased by introducing Yttria instead of brick is 13-38%
- The fuel savings are increased by introducing Yttria.
- The temperatures values of Yttria at different points are high compared to brick.
- The processing [melting] time observed with Yttria is lower than that of brick.
- Time being the temperature difference between the brick and Yttria were more and heat transfer to load is more.

By referring all above mentioned characteristics the Yttria coating concept is more efficient, time and fuel saving technology compared to steady state combustion technology with refractory fire bricks. This is currently being used in heat transfer industries to increase the fuel and time savings, as well as significantly helps to increase the efficiency of furnace.

NOMENCLATURE

T_1 Temperature at surface of crucible [^{o}C]

T_2 Temperature at fuel inlet [^{o}C]

T_3 Temperature at exit of flue gases [^{o}C]

D External diameter [m]

Re Reynolds number

U Uniform velocity [m/s]

Re =$2x10^5$

$\overline{Nu}$ Nusselt Number

P_r Prandtl umber

C Constant

n Constant

h Heat Transfer coefficient [W/m^2K]

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