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THERMAL AND COMPUTATIONAL FLUID DYNAMICS ANALYSIS OF AN OIL FIRED CRUCIBLE FURNACE DURING SECONDARY ALUMINUM SMELTING

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Abstract: *Thermal and computational fluid dynamics (CFD) analysis were explore with knowledge based software such as Solid Works and ANSYS workbench 14.0 for modeling and simulation of an Oil fired crucible furnace used for aluminum secondary smelting. Thermal analysis gives the maximum heat flux and directional heat flux as 8.7596W/mm^2 and 8.0349 W/mm^2 respectively. CFD simulation shows that the effect of the process parameter on the furnace components is as a result of furnace factors. In brevity theoretical calculations of thermal stress up in the furnace and heat transfer to crucible conform to the modelled results.*

Key words: *Crucible furnace, furnace factor, secondary aluminum smelting, thermal analysis, computational fluid dynamics.*

Termička i računska analiza dinamike fluida u loncu za loženje ulja tokom sekundarnog topljenja aluminijuma. *Analiza termičke i računske dinamike fluida (CFD) istražena je pomoću softvera zasnovanog na naučnim principima, kao što su Solid Vorks i ANSIS workbench 14.0 koji se koriste za modeliranje i simulaciju stanja peći na lož ulje koja se koristi za sekundarno topljenje aluminijuma. Termička analiza prikazala je maksimalni toplotni tok i usmereni toplotni tok u vrednostima od 8,7596 W/mm^2, odnosno 8,0349 W/mm^2. CFD simulacija pokazuje da je efekat procesnog parametra na komponente peći rezultat faktora peći. Ukratko, teorijski proračuni toplotnog naprezanja u peći i prenosa toplote u lonac odgovaraju modeliranim rezultatima.*

Ključne reči: *Lonac u peći, faktor peći, sekundarno topljenje aluminijuma, termička analiza, računska dinamika fluida.*

1. INTRODUCTION

Secondary non-ferrous smelting furnaces come in varied types, shapes, and sizes. The overall furnace efficiency of energy transfer in a melting process is a combination of furnace factor (percentage of total available energy that is actually absorbed by the metal during a melt cycle. and available energy (energy not loss when the flue gases leaves the furnace and hence is theoretical available to transfer to the metal). The furnace factor is a function of furnace type, refractory type, number and location of burners relative to the product and flue duct, location and size of the flue duct, flue gas volumes, and residence times available for completion of heat transfer. In simple words, it is a measure of the effectiveness of a furnace to transfer energy into the metal [1].

However, the melting and heat treatment of metal in foundries is very important in manufacturing process [2,3]. One of the most widely used furnaces is the oil fired crucible furnace. The oil fired crucible furnace uses the combustion of diesel as a fire source to heat the crucible and melt the solid metal [4]. A functioning furnace undergoes four interactive processes namely: flow, combustion, heat, and mass transfer. Heat transfer is only one process in the furnace, for which an exact solution cannot be obtained unless four groups of equations, corresponding to the four processes, are solved simultaneously. Thus, due to inherent complexity, strictly theoretical analysis is impossible. Evaluation of the thermal performance of fuel-fired furnaces is dependent on an accurate calculation of radiant exchange between the combustion products, walls and stock within the heating chamber. This calculation is highly complex; however, with the increasing availability of high speed digital computers it is becoming feasible to employ numerical methods for the calculation and prediction of important furnace parameters to determine furnace efficiency [5].

In an ideal furnace, all energy produced is usually utilized, but this is practically unachievable and there is no thermal processing equipment with efficiency of 100% [6] due to heat losses. These furnace losses include: heat storage in the furnace structure, losses from the furnace outside walls or structure heat transported out of the furnace by the load conveyors, fixtures, radiation losses from openings, hot exposed parts, heat carried by the cold air infiltration into the furnace and heat carried by the excess air used in the burners [7- 9]. Global energy and environment policies push manufacturers towards increasing the thermal efficiency of thermal equipment while reducing emissions from technological processes. The current trend in the operation of these types of thermal aggregates is air-fuel combustion, in which fuel is combusted with oxygen-enriched air or oxy-fuel combustion. Some studies agreed that an important factor in aluminum melting processes characterized by increased oxygen concentrations is represented by the increase of combustion temperatures in the furnace work area [9,10]

Mohammed [5] worked on investigation into the effect of changes in furnace operating conditions by employing the application of the 'well-stirred furnace model. Saha and Baukal [9] in their study presented an optimized type of the burner known under the commercial name RAPIDFIRE TM, manufactured by Air products, Olenyi et al [11] studied the design and thermal analysis of crucible furnace for non – ferrous metal using clay bricks and kaolin as refractories, Joseph et al. [12] examined the effect of heat on refractories used for the lining of the wall of crucible furnace. Jablonsky et al.[13]worked on the effect of increased oxygen on the combustion process and heat transfer, his result was attributed to the increase in combustion temperature caused by the increase in oxygen concentrations in the oxidizer, which affect only the fuel combustion kinetics [14-16].To prevent these losses, materials that can retain and conserve heat known as refractory materials are therefore used as lining materials for the furnaces [17] while slag fluxes that can also reduce melt loss are utilized [18]. Refractory materials are porous, multi-component and heterogeneous; that are composed of thermally stable mineral aggregate, a binder phase and additives [19,20].

2.0. MATERIALS AND METHOD

2.1 Material Selection for furnace

A 10 kg aluminum crucible furnace was designed majorly to melt aluminum and other non-ferrous metals (Figure 1) with efficiency of 29.70% which is within the efficiency range of conventional furnace, while heat transfer coefficient obtained as 4.48W/m^{2}K [21]. Compositional analysis of the mild steel plate used for the construction of furnace is shown in Table 1.

C	Si	Mn	P	S	Cr	Msb	Ni	Al	Cu	Zn	Fe	V
0.2267	0.2361	0.0412	0.0412	0.0616	0.1343	0.0212	0.1014	0.0025	0.2588	0.0059	98.095	0.0027

Table 1. Compositional analysis result of Mild Steel plate (MS)

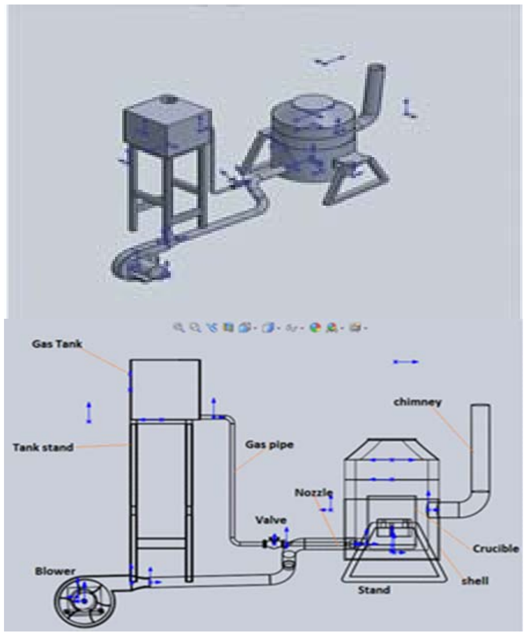

Fig. 1. 3-D model of the furnace and wire frame of furnace assembly

2.2 Modelling and Thermal Analysis (TA) of Oil Fired Crucible Furnace

The rate of heat transfer across the crucible furnace depends on the thermal properties of the refractory material and the interface characteristics. Design scenarios were created for the thermal analysis of the fuel fired crucible furnace [20,21]. Total heat flux (THF) and directional heat flux (DHF) of the graphite crucible and the diesel crucible furnace were analyzed with the information of their thermal properties culled from an engineering software (GRANTA 2011) (Table 2).

2.2.1 Procedure of the Analysis

The methodology for the transient thermal analysis of the aluminum crucible furnace is as follows:

Solid works software was used to generate the model then was further imported to the ANSYS workbench as seen Figure 4. The thermal properties of the crucible pot, lining materials properties and the casing metal properties were built in the engineering data from the information given in Table 2 and set up for the analysis was done. Finite element (FE) mesh on the model was generated as seen in figure 3, with boundary conditions (Table 5) imposed on the model problems for final solution.

Material properties	**Clay Bricks**	**Alumina**	**Mild steel**	**Graphite crucible**
Density	2100kg/m^3	3980 kg/m^3	7900kg/m^3	7250kg/m^3
Melting	1230^{o}C	2100^{o}C	**1510**°C	**2250**°C
Maximum service temperature	927^{o}C	1300^{o}C	420°C	1450 °C
Thermal conductivity	0.73W/m^{o}C	38.5W/m^o C	55W/m°C	44W/m.°C
Specific heat capacity	850J/kg^{o}C	820J/kg^o C	520J/kg.°C	495J/kg.°C
Thermal expansion coefficient	8*10^{-6} Strain/^{o}C	7.9*10^{-6} Strain/^{o}C	1.4e-5 strain/°C	1.25e-5, strain/°C

Table 2. Thermal properties of furnace components (Granta CES EDU PACK, 2011**)**

2.2 Computational Fluid Analysis (CFD)

CFD is based on the Navier-Stokes equations which describe how velocity, pressure, temperature and density of a moving fluid are all related. CFD gives an insight into flow patterns that are difficult, expensive or impossible to study using traditional experimental techniques [22,23]. Computer aided engineering software (Solid works) was used to generate the model in Figure 4 and Figure 8 that was imported into ANSYS fluent 14.0 and the CFD analysis was conducted with the ANSYS Fluent software package [24, 25]

2.2.1 Methodology

1) Solid works software was used to generate the model
2) The model was further imported to the ANSYS fluent 14.0 workbench.
3) The CFD analysis of the fluid flow in the crucible furnace pot, refractory linings were built in the engineering data as seen in Table 2
4) The set up for the analysis were done also.
5) A finite element mesh on the model was generated as seen in figure 8
6) The mesh was checked of errors and ensure consistency with the units used for simulations
7) Model was define (solver run model) with properties of the fluid (Table 4)
8) The boundary conditions were imposed on the model as seen in Table 5
9) The problems were finally solved.

Assumptions: The following assumptions have been taken while performing a solver run

Working fluid	**Heat Transfer Model**	**Turbulence Model**
Air at 750°C	Thermal Energy	K-Epsilon
Domain assumed is stationary		
Energy equation, and Viscous model		

Table 3. Assumptions for computational model

Viscosity	**Specific heat**	**Conductivity**	**Thermal expansivity**	**Density**
1.09e-5 Ns/m^2	1004.4 J/kg-K	0.03241 W/mK	0.003356/K	1.2 Kg/m^3

Table 4. Fluid Properties

S/N	**Description of item**	**Value/units**
1	Pre heating temperature	350°C
2	Pouring temperature	750°C

Table 5. Boundary conditions for the transient thermal analysis

3.0 RESULT AND DISCUSSION

3.1 Theoretical Calculation of Heat Flow in Crucible and Thermal stress up

The Detailed dimensions of the furnace drum follows the developed and designed oil fired crucible furnace by Owolabi et al [21]. The furnace drum was made from a 3mm thick mild steel plate rolled into a cylinder of diameter of 510 mm and height 470 mm with the overall combustion space of diameter 495 mm and height 320mm.

The Detailed dimensions of the furnace drum are as follows:

a) Height of the furnace drum before laying bricks (h) = 470 mm,
b) Height of combustible space of the furnace drum after laying of bricks (h1) = 405 mm,
c) Internal diameter of the furnace drum before laying of bricks (d) =510 mm,
d) Internal diameter of the furnace drum after laying of bricks (d1) = 495 mm,
e) Inlet diameter of the burner nozzle = 30mm,
f) Outlet diameter of the burner nozzle = 35mm,
g) Height of the cover = 120 mm,
h) Total height of the drum = height of drum + height of cover = 470 + 120 = 590 mm,
i) Diameter of the chimney hole (on cover) = 100 mm
j) Thickness of the metal plate = 3 mm,
k) The Total height of the crucible furnace = 470+120=590 mm,
l) The height of the crucible body = 170 mm,
m) The thickness of the crucible = 10 mm
n) The diameter of the crucible = 150 mm,
o) The thickness of the Durax lining= 50 mm
p) Height of furnace cover = 120 mm,
q) Diameter of furnace cover = 510 mm

$Heat\ transfer\ to\ the\ crucible\ per\ seconds\ Q_C$

Deduce From fourier law in equation 18

$$Q_C = K_c \frac{A\Delta T}{x} \ldots \qquad (1)$$

$Q_C = Heat\ transfer\ to\ the\ crucible$,
$K_c = thermal\ conductivity\ of\ crucible$
$x = thickness\ of\ crucible$

$$A = 2\pi r(r + h) \qquad (2)$$

$$A = 2x3.142x75(75 + 170) = 115468.5mm^2 = = 0.116m^2$$

$$Q_C = 0.84\ x\ \frac{0.116(1023-973)}{0.01} = 487.2kj/s$$

$Thermal\ stress\ setup\ in\ the\ furnace\ wall$

Assuming a steady state condition is obtained from the expression suggested by Harvey (1982) as

$$\sigma l_a = \sigma t_a = \frac{\alpha E(T_a - T_b)}{2(1-v)} = \frac{-\alpha E\Delta T}{2(1-V)} \qquad (3)$$

$\sigma = allowable\ stress\ of\ the\ material$,
$E = modulus\ of\ elasticity\ of\ the\ material$,
$v = possion\ ratio$,
$\Delta T = change\ temperature$,
$K_1 = Specific\ thermal\ analysis$,
$T_a = ambient\ temperature$

$$\sigma l_a = \sigma t_a = 3.9x10^{11}x7.9x10^{-6}\left(\frac{298-933}{2(1-0.26)}\right)$$

$$= 3081000\left(\frac{-645}{1.48}\right) = 1342699800 = = 1.34\ x10^9\ N/m^2$$

3.1 Transient Thermal Analysis of Graphite Crucible

Figure 2 shows that the heat flux in the graphite crucible pot has a maximum of 5.0916 W/mm^2, with minimum heat flux of 0.00014075W/mm^2 which indicates that the crucible is a good conductor of heat. The maximum heat flux is observed inside the crucible while the minimum heat flux is seen on the edge of the crucible pot in the outer region. Heat flux of the crucible is a function of the material composition and also the environment (amount of energy evolve or absorbed). From Fig. 2, the crucible has a maximum directional heat flux of 5.0418 W/mm^2 with minimum directional heat flux (-4.9954 W/mm^2). Maximum directional heat flux is seen more on the pot that faces the burner along the x axis.

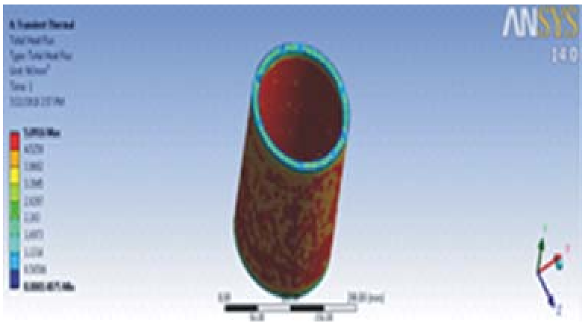

Fig. 2. Total heat flux of TA of the Crucible

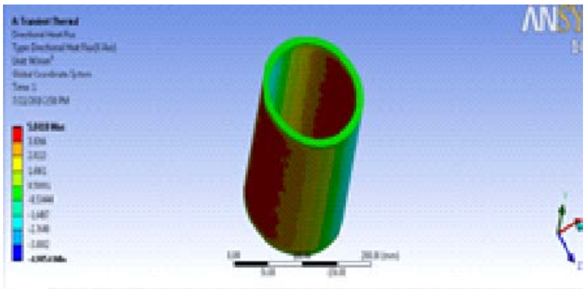
Fig. 3. Directional heat flux of the TA of the Crucible

3.2 Thermal Analysis of Oil fired Crucible Furnace

The mesh size was determined starting from coarse to fine mesh to achieve a convergence in result, as seen in Figure 4 in which nodes of 123056 and elements of 65029 was obtained. Furnace consist of the crucible, refractory wall and casing of the furnace which shows the elemental mesh to simulate the effect of fluid flow and heat distribution in the crucible furnace components (Figure 4). The maximum and minimum values of the total heat flux of the transient thermal analysis of the fuel (oil) fired aluminum crucible furnace is 8.7596 W/mm^2 and 3.4343E-5 W/mm^2 respectively as seen in Figure 5. As the flame temperature increases heat flux values distribution also increases inside the furnace gradient, maximum heat flux result is observed in the furnace which can be as a result of good emissivity and better conductivity of the refractory materials (alumina bricks and refractory cements) which agrees with Joseph et al [12], minimal heat flux is observed at the outer shell of the furnace and cover. Moreover region with minimal heat flux showed that the refractory lining has good insulating capacity which reduces heat losses to the outside casing [26], This process continues as long as the furnace is at an elevated temperature which is evident from the work of Atanda et al.[19].

In Figure.6, the maximum and minimum directional heat flux of the transient thermal analysis of the fuel crucible furnace is 8.0349 W/mm^2 and -8.281W/mm^2 respectively. The maximum directional heat flux is observed in the axis where the flame temperature is more concentrated in the combustion chamber; the furnace covered adjacent to the burner path shows high directional heat flux hence Increase in air preheat temperature improve heat flux and furnace efficiency which is in agreement with Mohammed [5]. Sectional view of the analysis is shown in Fig. 6 and Fig. 7 to understand the thermal flow in the furnace.

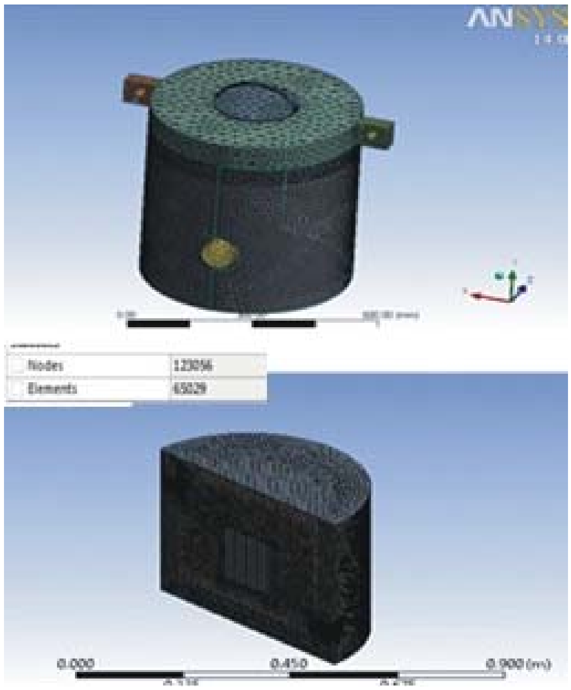

Fig 4. Finite element mesh of the oil fired Crucible furnace

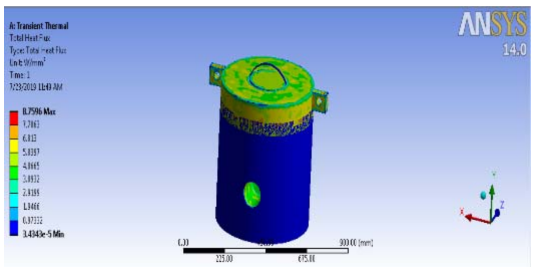

Fig. 5. Total Heat Flux of the TA Crucible furnace

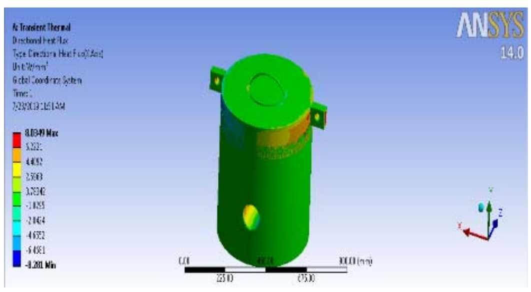

Fig. 6. Directional Heat Flux of the TA of oil Crucible furnace

3.4 Computational Fluid Dynamics Simulation

Figure 7 shows the contour of static temperature in the crucible furnace, temperature distribution at the burner interface of the crucible furnace being ~ 2130K is observed which is the highest. The sectional view of contours of static temperature, shows the temperature distribution on the refractory as seen in Figure 9, its distribution on the furnace casing (Figure 10) and its distribution on crucible pot (Figure 11). Figure 7, shows the 3D and 2D view, result indicates that the maximum temperature on the refractory wall is 1635K, heat loss through the wall of the furnace is a limiting factor for the refractory bricks to attain higher temperature, since the refractory bricks used (alumina bricks) has high conductivity. Figure 9 shows the sectional view of temperature distribution on the casing of the furnace (mild sheet), maximum temperature is seen in the region of the burner while minimum temperature is seen at chimney region. Figure 11, shows the 3D and 2D sectional view of the temperature distribution on crucible pot, maximum temperature is 1534K which is evidence more around the edge of the crucible.. From Figure 11 the fluid flow in the furnace component is evidently seen on the refractory bricks, minimum fluid movement is seen at the entry and exit region of the air fluid. In Figure 8, the contours of dynamic pressure, which is the effective pressure caused by the movement of the fluid as a results of the excitation caused by the applied heat from the burner are shown with minimum pressure of 1.67×10^{-17} Pa and maximum pressure of 1.7×10^{3} Pa. As temperature increases there is positive impact on the pressure (pressure law). Figure. 12 shows the 3D and 2D sectional view of pressure distribution in the furnace components, maximum pressure is prominent around the upper area within the furnace combustion chamber, where there is more pressure build up as a result of excitation caused by the applied heat and air from the burner. Minimum pressure is observed in the crucible since the crucible is open within the furnace environment with less pressure build up.

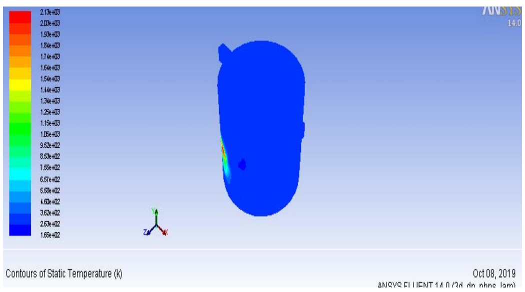

Fig. 7. Contour of static temperature

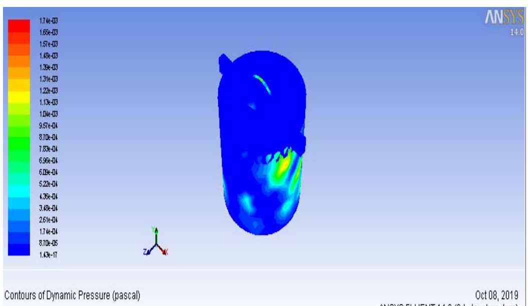

Fig. 8. Contour of dynamic pressure

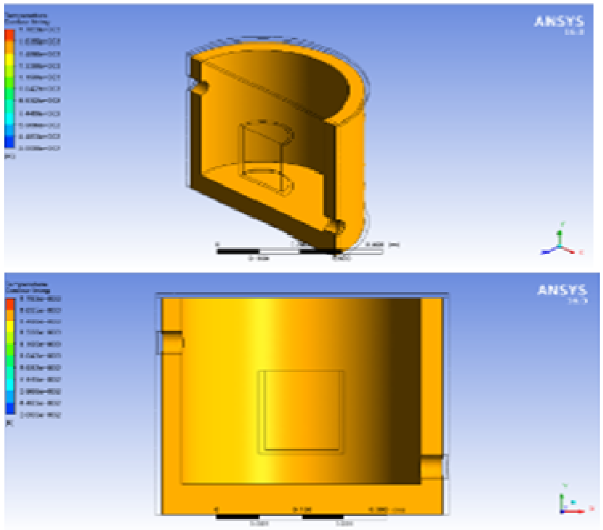

Fig. 9. 3D and 2D View of temperature distribution on refractory wall

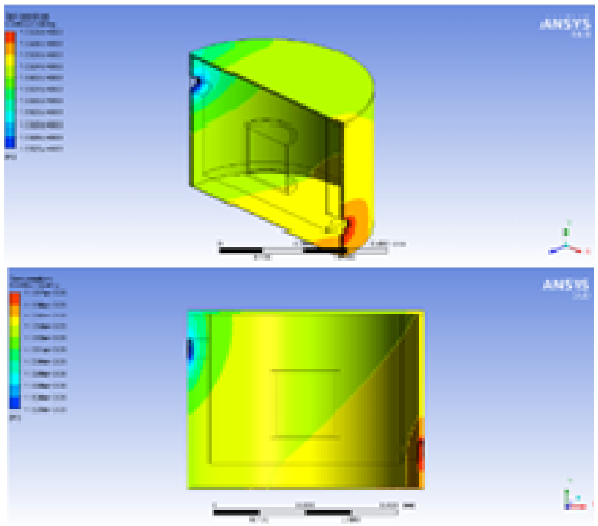

Fig. 10. 3D and 2D sectional view of temperature distribution of Furnace casing

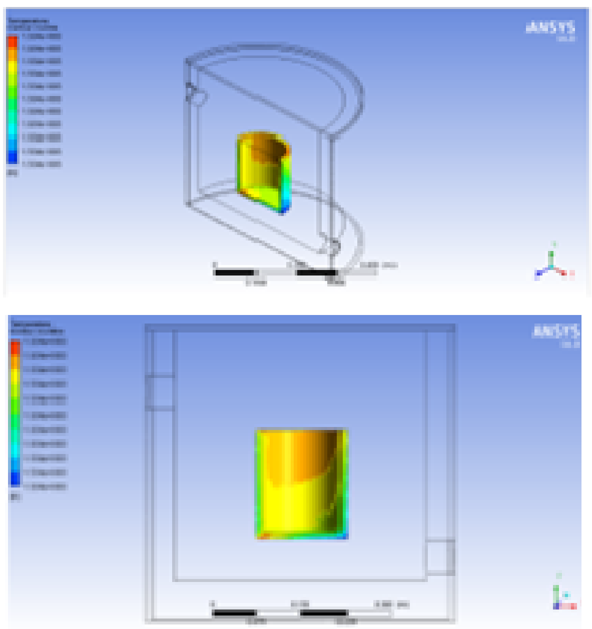

Fig. 11. 3D and 2D sectional view of temperature distribution on crucible pot

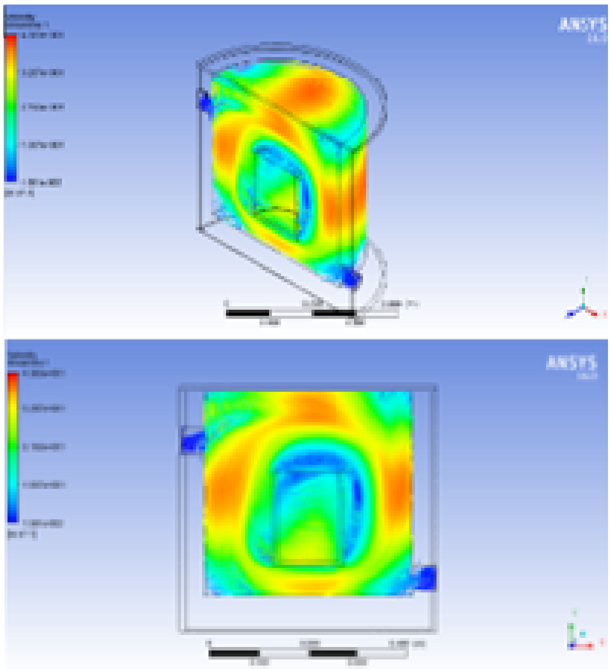

Fig. 12. 3D and 2D sectional view of velocity fluid flow in a crucible furnace

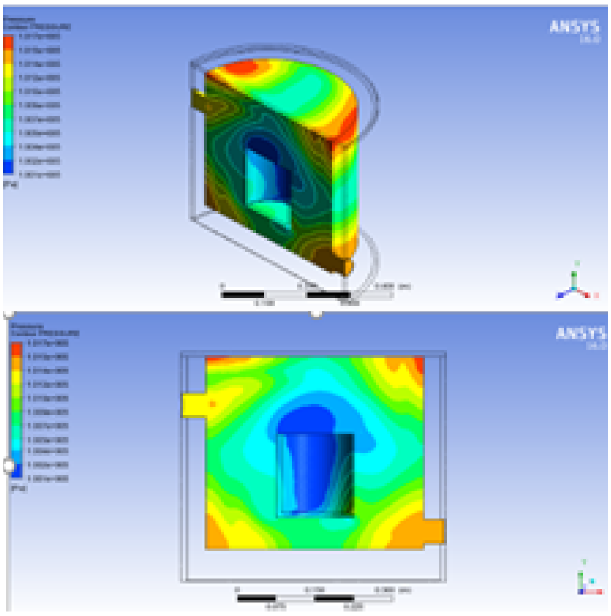

Fig. 13. 3D and 2D sectional view of pressure distribution in a crucible furnace

4. CONCLUSION

Detailed transient thermal analysis and CFD have been carried out with ANSYS workbench 14.0 on an Oil fired crucible furnace. The thermal properties of the crucible, furnace casing and refractory bricks were carefully selected using Granta CES Edu pack (2011). This study established pressure and temperature as important operating parameters with computational fluid dynamics to improve furnace efficiency during smelting operation, from the results of the analysis, it was observed that knowledge based software can aid accurate prediction of heat flux , directional heat flux, fluid flow in furnace with varying operating parameters. Theoretical calculation of designed furnace results of heat flow in furnace validate the result from the simulation of heat flux and CFD analysis. Hence efficient consideration of the furnace factor and process parameters geared towards optimization of furnace efficiency and melt loss reduction can be achieve by application of modelling and simulation.

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