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Modeling, Simulation and Thermal Analysis of Electric Resistance Furnace used in the Heat Treatment of Clay Based Ceramics

Binod Adhikari [a], Rajendra Shresetha [b], Bijendra Prajapati [c]

[a, b, c] *Department of Mechanical and Aerospace Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
✉ [a] vnodadhikari@gmail.com, [b] rsfluid@hotmail.com, [c] bijendra.prapjapati@pcampus.edu.np

Abstract

Electric resistance furnaces can replace the traditional fuel fired furnaces in the pottery industry as these furnaces utilize the electricity to heat treat the clay based ceramics in a uniform manner. In this study, an electric resistance furnace is modeled and an attempt to study the thermal behaviour of the furnace is made.The temperature distribution in the walls, the furnace environment and the material to be treated are the scope of this study. The results were then verified with the experimental data obtained from the field visit for the outer wall temperature and the furnace internal temperature. Computational study show the temperature deviation on the walls of the furnace below 15% and internal temperature below 5% than that of the experimental value. Further, an attempt to reduce the external wall temperature and heat flux is made by certain variations in the insulating material.The alteration of the insulation by constant total thickness method adopted reduces the heat flux by 29.4% while for meeting the industrial standards, minimum addition of 40mm of insulation is needed. The study is aimed to provide optimum design for reconstruction of the worn out furnaces as well as the improved future designs of the furnace.

Keywords

Electric Resistance Furnace, Modeling, Simulation, Thermal Analysis, Heat Treatment, Clay-based ceramics

1. Introduction

Pottery industry is an energy intensive industry which involves the heat treatment of the clay based ceramics at high temperatures[1]. At present in Nepal, the traditional method of firing of the clay based ceramics using firewood or any other non-renewable sources in the pottery industry is being replaced by electricity in the electric resistance furnaces. These electric resistance furnace utilize a heating element which works on the principle of Joules law of heating[2].

The electric resistance furnace under study in this paper is simple in construction with the layer of refractory brick grooved on the inside in a regular manner to allow space for heating element. Outside the refractory brick layer is an insulation layer of ceramic fibre blanket and this total entity is enclosed in a steel casing. A k-type thermocouple is fitted inside the furnace for the measurement of the internal temperature of the furnace when it is operating. The electric resistance furnace preserves the cultural aspect of ceramics production, so it is easily accepted by the people involved in this industry. Since heat treatment is the most vital process of ceramics production, the study of the heat transfer process in these furnaces would prove useful for the improved design, better working as well as its enhanced performance ultimately leading to energy saving.

1.1 Heat treatment process

The process of ceramics production involves molding the clay, drying and firing. Firing process requires treatment to higher temperatures and is carried out in two phases; bisque firing and sintering or high temperature firing. Firstly, bisque firing is done at around 850°C. The clay based ceramics is then cooled before glazing and then sintering is done inside the furnace at around 1050 to 1200°C. The total heat treatment cycle in the furnace completes in three stages; the heating-up stage, soaking stage and cooling stage. [2].

A typical sintering curve is shown in Figure 1.The ceramics is heated to around 1050 to 1200°C, kept at that temperature for some time and then cooled to room temperature.

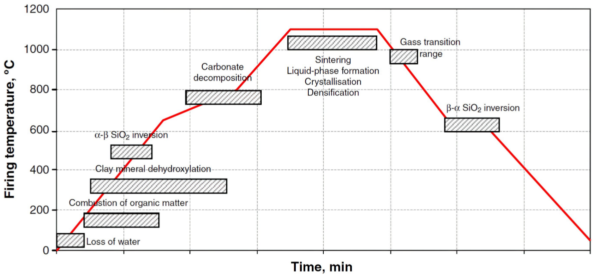

Figure 1: Typical firing curve with the physico-chemical reaction for traditional ceramics[3]

The present study is focused on the heating of the glazed clay based ceramics in sintering or the second firing process.The study is carried out to study the heat and temperature distribution in the furnace during the heating phase of the firing process to understand the furnace behaviour and working.

1.2 Furnace details

The furnace under study is a batch type furnace with air as the working fluid inside the furnace during operation. The final operation temperature reached in the furnace is around 1075°C at process completion, so it is a high temperature furnace[2]. The furnace operation time for second firing is around 11.5 hours and the rating of the furnace is 11.5kWh.

1.2.1 Furnace components

The major components of a high temperature electric resistance furnace are; heating element, refractory layer and thermal insulation. Other accessory devices such as pyrometers and thermocouples are needed for measurement of the temperature.

The heating material used in the furnace under study is Kanthal A wire which is an alloy of Iron (70-76%), Chromium (20-24%) and Aluminium (4-6%). The aluminium present in the kanthal wire forms an oxide layer at higher temperature and protects the wire from damage due to oxidation[4, 2].

Refractories are substances that can endure high temperatures and remain intact when exposed to corrosive liquids and gases in a furnace environment[5]. High alumina refractory brick was used in the furnace under study as the refractory layer.The thermal conductivity of the high alumina refractory brick varies from 0.12 to 0.22 W/(m K) with the increase in temperature.

Insulations are materials or combinations of materials which retard the flow of heat energy thus helping to reduce heat loss and increase the operating efficiency of the system[5]. The insulating material used in the furnace under study is ceramic fibre blanket whose thermal conductivity varies from the 0.039-0.117 W/(m K). The Seebeck effect-based thermocouple is the most widely used and practical method of sensing high temperature.The device used to measure the temperature inside the furnace under our study is K-type thermocouple which has combination of chromel and alumel alloys and can measure temperature up to 1250°C[2].

In this paper, an attempt to study the heat transfer process through the walls, the temperature and heat distribution inside the furnace during the furnace's operation is made. The aim is to study the behaviour of different components and suggest future methods to adopt during the construction of new furnaces or the reconstruction of the worn-out furnaces. Firstly, the thermal performance of the existing furnace is assessed experimentally and then later, a commercially available simulation software package, ANSYS Transient Thermal was used for computational study.The heat transfer process was studied as transient thermal process. A steady state thermal analysis was carried out for cross verification purpose.

1.3 Heat transfer theory

The mode of heat transfer in the walls of the furnace is conduction. The general three dimensional transient heat conduction equation in the Cartesian(x, y and z) coordinate system is given as[6, 7, 8, 9]:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)=\rho c_s\frac{\partial T}{\partial t} \tag{1}$$

In equation (1), the right hand side term represents the transient term and is the partial derivative of temperature with respect to time.

For steady state, the heat conduction equation in the Cartesian(x, y and z) coordinate system is given as[7, 8]:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)=0 \tag{2}$$

The heat conduction for heat flow in three dimensions is given by Fourier law as :

$$Q = kA\frac{dT}{dn} \tag{3}$$

where n represents the unit normal vector in the x, y or z direction.

For chambers or enclosures with no any fans, free convection occurs which may be laminar at lower temperatures and may transition to turbulent at higher temperatures. Since the temperature of the heating element is considered constant, the furnace interior can be modelled as the parallel plates with constant heat source[9].

The heat transfer between atmosphere and solid surface by convection is given by

$$Q_h = h\dot{A}(T_s - T_\infty), h = \frac{k}{L}.Nu_L \tag{4}$$

For laminar or turbulent free convection over a vertical plate, that is, for any Rayleigh number, the average Nusselt number is given by [7, 8, 9]

$$Ra = (Gr.Pr) = g\beta \frac{(T_i w - T_\infty i)}{\nu\alpha} * L^3 \tag{5}$$

$$\bar{Nu}_L = \left[0.825 + \frac{0.387Ra^{\frac{1}{6}}}{\left[1+(\frac{0.492}{Pr})^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right]^2 \tag{6}$$

The radiation that occurs through the outer wall of the furnace is calculated using the following relation:

$$Q_R = \varepsilon_i.A.T_s^4 \tag{7}$$

The firing of clay based ceramics in the traditional fuel fired furnaces have been studied but proper studies in the electric resistance furnace have not been carried out as seen from the literature. The electric resistance furnace eases the inspection process of heat treatment. It also eliminates the timely check of the fuel needed for firing. Also, the electric resistance furnace is environment friendly and there are no any flue losses to the surrounding. Hence, ensuring the proper construction materials, proper design for uniform heat and temperature distribution in the furnace would prove useful for increasing the operational efficiency of the furnace. Hence this study was carried out with the following specific objectives:

- To design a full scale and some simplified CAD models for the existing electric resistance furnace.
- To do a transient thermal analysis for studying the heat and temperature distribution on the furnace walls and inside the furnace.
- To study the conduction through furnace walls in a detailed manner.

Assumptions and limitations The heating coils are modelled as the thin strips of wire which achieve a constant temperature of 1300°C after certain time[10]. The heat transfer process in the walls of furnace is assumed to occur by conduction while the heat transfer process inside the furnace is studied as convection and radiation[11].The temperature measured by thermocouple is the temperature of the internal environment of the furnace. The effect of external environmental on the furnace operation and the effect of furnace on the external environment does not fall under the scope of this study. Also, the refractory brick wall is assumed as a single object and the cementing materials of the walls are not taken into consideration during the study of heat transfer process.

2. Methodology of study

The past works related to electric resistance furnace and its working, materials used in its construction, sintering process of ceramics, mathematical formulation and numerical simulation of the heat transfer processes occurring inside different furnace were studied extensively by taking reference from many research papers and articles on similar work.

2.1 Site and Experimental data

Few places in Bhaktapur district where electric resistance furnace have been installed were the possible sites for experimental study. Among them, Everest Pottery located at Sanothimi was chosen for experimental data collection.The condition of the furnace, materials used in its construction, its dimensions, its operation duration and condition, working temperature, loading conditions, surface temperature of the furnace wall during operation and the environment around the furnaces are the prime concerns in our study.

The study in this paper focuses on the heating process of second firing or sintering. The total time taken for the completion of the heating process was noted using a stopwatch. For the heating phase in the furnace, a K-type thermocouple fitted inside the furnace gave the reading for the internal temperature of the furnace. Similarly, an infrared thermometer gun was used to measure the temperature of the furnace wall at various sides and locations. The average value was calculated for the temperature for front and side walls of the furnace. The ambient temperature was taken to be

25°C and the total time of 11.5 hours, that is, 41400 seconds was taken for the process completion. The current passing through the heating element was measured using the clamp ammeter and from the constant supply voltage value of 220V, the resistance of the wire was calculated.

Table 1: Time-temperature data for the furnace

Time(s)	Temperature(°C)		
	Internal	LS wall	Front wall
0	25	25	25
900	78	28.49	27.74
5400	257	37.7	33.36
10800	465	48.38	51.91
16200	618	58.87	70.89
21600	742	70.578	77.4
27000	865	82.68	91.13
32400	954	94.39	101.9
37800	1027	104.68	108.39
41400	1075	111.7	114.7

The data in Table 1 show the values of temperatures of the internal and external wall at different time intervals. The working temperature of the heating element is taken to be 1300°C which is the maximum continuous operating temperature of the Kanthal wire[4].
The dimensions of the furnace interior as well as the thickness of the components that make up the wall of the furnace was measured using the measuring tape and vernier callipers. For the loading data of the batch type furnace, each of the component was weighed using a weighing machine before loading it into the furnace. The furnace is loaded symmetrically in two stacks one over the other with the help of slabs and blocks. A typical case of loading is provided in the Table 2.

Table 2: Typical loading data for the furnace

S.No.	Components	Qty	Weight(kg/piece)	Total weight(kg)
1	Slab	20	7	140
2	Block	54	0.17	9.18
3	Big plate	20	1.118	22.36
4	Small plate	20	0.756	15.12
5	Small disc	80	0.096	7.68
	Total			**194.34**

2.2 Furnace model

A full scale CAD model of the electric resistance furnace was designed using the designing software, SOLIDWORKS 2019. A furnace of inner dimensions 920 mm × 640 mm × 640 mm is considered which has a top opening cover. The cover is 180mm thick and has a layer of insulation only that is reinforced by small wires for mechanical stability. The layer of the refractory is 115mm thick while the insulation layer is 65mm thick on the walls.The total furnace is enclosed in a steel casing.

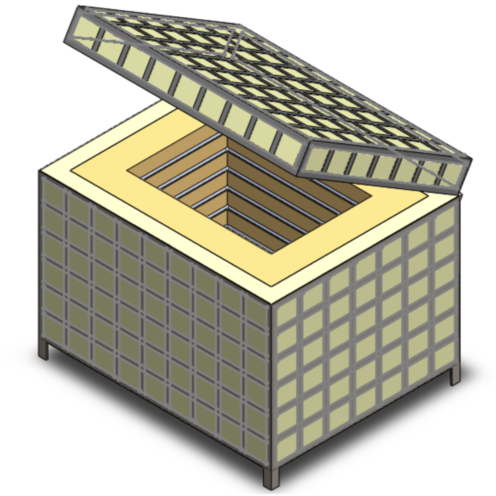

Figure 2: Full scale CAD model of the furnace

2.3 Computational study

The computational study is carried out using ANSYS Transient Thermal. It utilizes the finite element approach for the analysis of the model under study. The first step is to design the simplified models of the furnace taking into consideration the symmetry of the furnace walls.

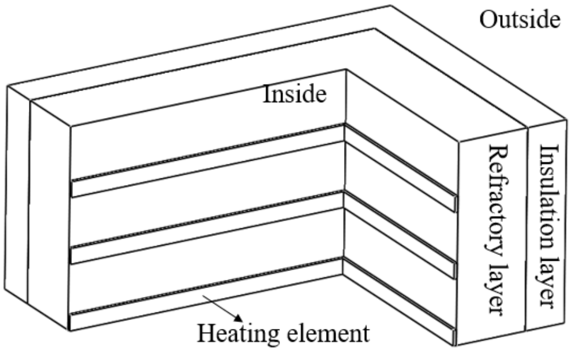

Figure 3: A simplified model consisting 1/8th part of furnace

One-eighth part of the furnace was modelled as shown in the figure 3.The heating element is modelled as thin strips of wire on the inner wall of the furnace.

The dimensions of the simplified model is 460mm x 320mm x 320mm.The simulation study on this model is simply for the study of heat transfer process through the walls. The heat transfer process is then studied by adding air domain to this simplified model. In the next step a symmetrical object is placed at the centre in the next object and the heat transfer phenomena is studied.

2.3.1 Meshing

Meshing is the procedure of splitting the computational domain into smaller regions to facilitate the iterative solving of the complex heat equations. This is done by turning these complex heat equations into simple algebraic equations.The meshing was done in ANSYS 2022 R1 version by controlling the various global and local mesh controls.The preciseness of the solution obtained can be increased by increasing the number mesh elements or sub domains. But very fine meshing requires greater computational time, cost and effort. Hence, a mesh independence test is carried out to apply the optimum mesh sizing that requires the least computational cost and time without compromising the desired accuracy of the solution.

2.3.2 Boundary conditions

The boudary conditions used for the computation are as shown in the table 3

Table 3: Boundary conditions and parameters

Parameters	Value	Units
Outside convection coefficient	5	W/m2K
External ambient temperature	298	K
Initial internal temperature	298	K
Initial temperature of outside wall	298	K
Thickness of brick layer	0.115	m
Temperature of the heating coil	1573	K
Thickness of insulation	0.065	m

2.3.3 Solution and post processing

The total process of the heat treatment completes in 11.5 hours. So, it is not be possible to simulate the whole process with each and every seconds considered. So, the analysis is done by taking certain time steps. The time dependent solver is used to obtain the solution for the model from 0 to 41400 seconds by taking 10 steps with an initial step of 900 seconds and then every step of 5400 seconds. Each of these 9 steps were divided into 180 sub steps with a single sub-step of 30 seconds. After defining the time step, other boundary conditions were applied and the heat transfer analysis is carried out in ANSYS Transient Thermal.

3. Results and discussion

The experimental and computational study were carried out separately which helped to come to the following results.

3.1 Experimental results

The temperature distribution inside the furnace is shown in the figure 4. From the figure 4, we can see that the temperature rise rate is more in the first few intervals while the temperature rise rate gradually decreases as the heat treatment proceeds towards the completion. In the first 900 seconds, the temperature rise rate is 3.53°C/min which decreases up to 0.80°C/min for the final time step.The initial temperature is 25°C and the final temperature reached is 1075°C when the process completes. The curve is not horizontal and has a positive slope at the completion of the sintering process so it can be deducted that the process does not reach a steady state at its completion.

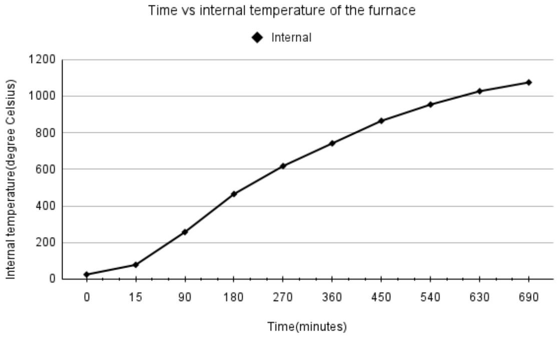

Figure 4: Time vs internal temperature plot for the furnace

The figure 5 shows that the temperature distribution on the outer wall of the furnace. Initially the wall is at the same temperature as the ambient air temperature of 25°C. This temperature rises up to 111.7 °C for the lateral walls while the the temperature is 114.7°C for the front wall. The higher temperature on the front wall can be attributed to the small exhaust hole present on the furnace front wall which is only closed after the furnace reaches the temperature of around 250°C to let the moisture to pass out of the furnace as vapour.

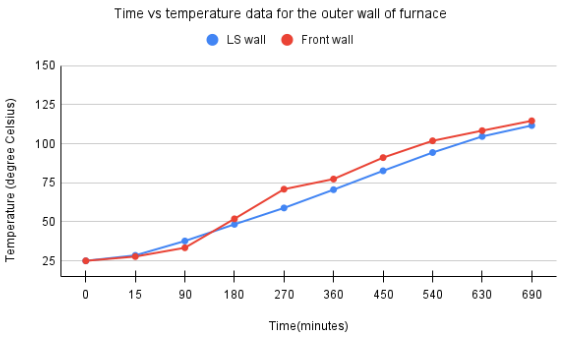

Figure 5: Time vs external wall temperature plot for the furnace

3.2 Computational results

The computational study was carried out in a step-wise manner in the ANSYS Transient Thermal and Steady state Thermal. The steady state thermal analysis was done for simply the cross verification of the fact as observed from the experimental data that the process does not reach the steady state at its completion.

Transient thermal analysis: The heating element, which is assumed to be at constant temperature of 1300°C transmits heat to the walls and air by conduction and convection respectively. The heat transfer between the heating element and the object at the centre occurs by radiation as well which is dominant at higher temperature [12]. All the boundary conditions were applied to the simplified model of the furnace with a symmetrical thin walled object placed at the centre and the simulation was run. The resulting temperature distribution of the whole domain is as shown in Figure 6.

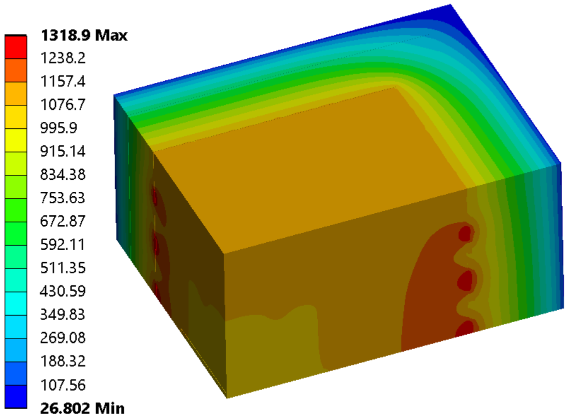

Figure 6: Temperature profile on the model of furnace

It can be seen that the highest temperature of 1318.9 °C is reached in the heating element. The lowest temperature,26.902°C is at the corner edge of the L-shaped wall on the outer wall of furnace. Small circular regions of constant temperature are formed around the heating element in the air domain present inside the furnace. The temperature is seen to gradually decrease in the wall region towards the outside. The minimum temperature of the domain 990.74°C while the maximum temperature is 1318.9°C which occurs in the vicinity of the heating element. The average temperature of the inside air of furnace is 1132.6 °C at the process completion.

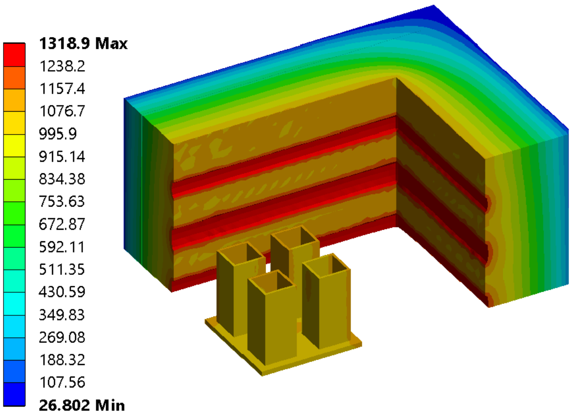

Figure 7: Temperature profile on inner walls and on central object

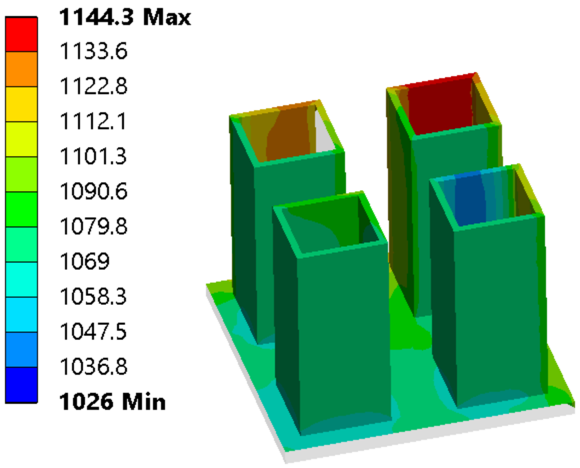

Figure 8: Temperature variation on the central object

The temperature of the central object varies from minimum of 1026°C to maximum of 1144.3°C. The maximum temperature is on the side of the object that faces the heating element while the minimum temperature occurs on the body which lies more towards the centre of the furnace and does not directly face the heating element. The average temperature of the object is 1087.2°C. This average temperature is does not vary much from the experimental data of the temperature at the process completion. The difference may be attributed to the central object being modeled as the long hollow objects instead of the real ceramic object which have flat base and low height.

Furnace walls The maximum average temperature of the outer wall of the furnace is 96.86°C while the minimum value is 26.80°C. This temperature is reached on the shorter side of the outer wall while the temperature on the longer side is 96.38°C, which is slightly lower than that on shorter side. The variation of maximum heat flux on the outer wall is as shown in the Figure 9. The maximum value of heat flux is 666.68 W/m2 and the minimum value of the heat flux is 9.03 W/m2.

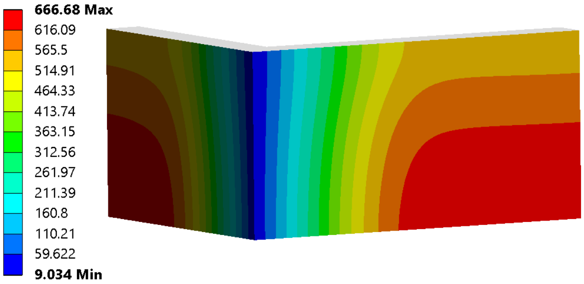

Figure 9: Heat flux variation on the outer wall of furnace

The value of temperature on the outer wall of furnace is high as compared to the industrial standards which suggest the wall temperature to be between 60-70°C[13]. So, a detail analysis of the furnace wall materials and thickness was carried out in an attempt to reduce the outer wall temperature and hence the heat loss through the outer walls of furnace[14] Since, refractory bricks are produced in standard dimensions and the ceramic fibre blankets come in rolls of different thickness, the only variation of thickness of wall can be achieved by varying the thickness of the insulation.

Two approaches are made in an attempt to reduce the heat loss from the walls. The first approach is constant total thickness approach in which the total thickness of wall, that is, total thickness of 18cm is kept constant. 20mm thickness of ceramic fibre blanket is replaced by different insulation materials and air gap combination.[5]. Thermal mass values were calculated for five different insulation materials with the working temperature not exceeding their maximum temperature of safe use. 10mm layer of clay adjacent to refractory brick and a 10mm of air gap maintained between the clay and ceramic fibre blanket insulation is found to reduce the temperature as well as heat flux on the outer wall of the furnace by a considerable amount.

The second approach is variable volume approach in which the thickness of existing insulation was increased until the maximum temperature on the outer wall is 70°C. A ball park value was obtained from the one dimensional transient thermal analysis by numerical approach and repeated simulations were carried out to obtain that value by altering the thickness.Addition of extra 40mm layer of insulation would reduce the outer wall temperature to 70°C.

3.3 Comparative results

The temperature variation for the outer wall of the furnace from experiment and computation are plotted in the figure 10. The difference between the temperature is zero at the beginning of the process. At the time of completion of the process, the average of the experimental value of temperature is 113.2°C while the computational value is 96.868°C. This difference of 16.33°C is around 15% less than the experimental value.

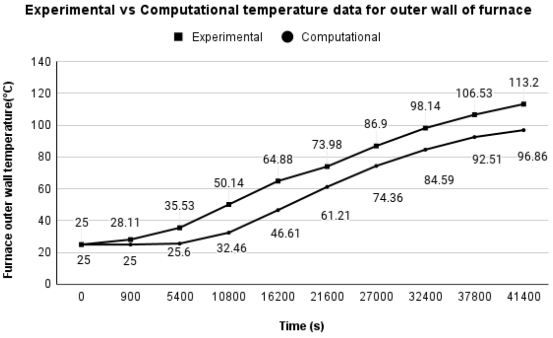

Figure 10: Experimental vs Computational temperature data for the outer wall of furnace

This result suggests that the either the material is not as specified in the specifications, the furnace is worn out, the wall materials have defects or the wall materials are not joined together properly. Though the heat conduction through the binding wall material is not taken into consideration in our study, the temperature difference observed cannot be attributed to the binding material only.

This result also suggests the fact that the insulation might be insufficient. As seen from the literature, the thickness of the wall of industrial grade furnace is around 300mm [13], but the electric resistance furnace under study has only 18mm thick insulation.

Furnace walls alteration: The variation of the maximum outer wall temperature for the existing furnace wall with a total of 105mm thickness of ceramic fibre insulation and the constant total thickness of wall with 10mm of clay and 10mm of air gap maintained adjacent to the refractory brick are shown in the Figure 11. The results suggest that the maximum outer wall temperature can be decreased from 96.86 to 77.89°C with the clay and air gap at the middle of the furnace. Similarly, the temperature is reduced to 70.19°C from 96.86 °C by adding a 40mm layer of insulation outside of the existing wall of furnace.

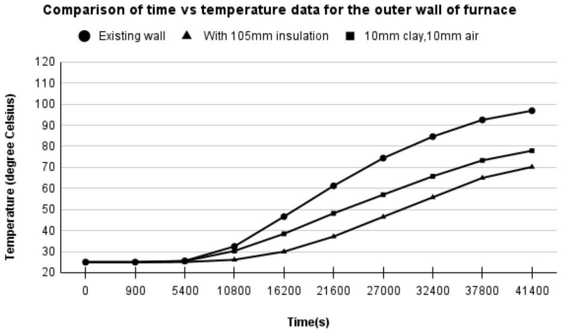

Figure 11: Time vs temperature data for different wall models

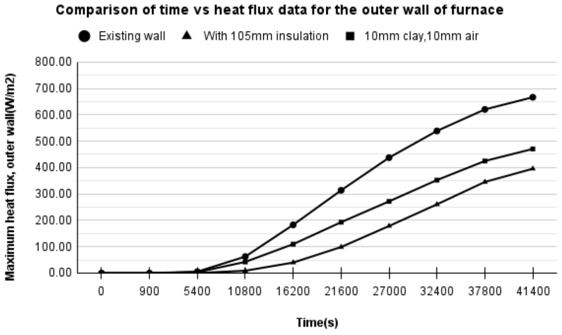

Figure 12: Time vs heat flux data for different wall models

The heat flux value also suggests the same result. The maximum heat flux passing out of the wall of existing furnace wall is 666.68 W/m2 which can be reduced to 470.67 W/m2 for the combination of clay and air gap adjacent to refractory brick for constant wall thickness. For the thickness of 40mm insulation of ceramic fibre blanket added, the maximum heat flux value can be reduced to 395.63 W/m2. The reduction in the maximum heat flux on outer wall of furnace is 40.06 % for clay-air gap combination while for the added 40 mm layer of insulation, the reduction in heat flux is 40.67%.

4. Conclusion

The following conclusions can be drawn from this study that involves both experimental and computational study.

- The experimental outer wall temperature on the front wall of the electric resistance under study is higher than that on the other walls of the furnace.
- Transient thermal analysis of the furnace shows 15% lower value of the maximum external wall temperature for the furnace than the value obtained from experimental data.
- The average value of the internal air or wall temperature from computation is found to be 1132.6°C.
- The average temperature of the thin walled object placed at the centre is 1087.2°C.
- The replacement of 20mm insulation by a combination of clay and air gap adjacent to the refractory brick layer reduces the heat flux on the outer wall by 29.4%
- The thickness of insulation of the ceramic fibre blanket to be added on the outside of existing furnace to obtain a temperature for meeting the industrial standards of 70°C is 40mm.

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References

[1] Prakash Shrestha. Challenges and scopes of pottery industry. *Pravaha*, 24(1):147–158, 2018.

[2] C Barry Carter, M Grant Norton, et al. *Ceramic materials: science and engineering*, volume 716. Springer, 2007.

[3] Salvador Ferrer, Ana Mezquita, Maria Pilar Gomez-Tena, Cristina Machí, and Eliseo Monfort. Estimation of the heat of reaction in traditional ceramic compositions. *Applied Clay Science*, 108:28–39, 2015.

[4] Primatryck. *Kanthal Handbook: Heating alloys for electric household appliances*. Reklam Centre 03057, 1-a-4-3 edition, 2003.

[5] Indian Bureau of Energy Efficiency. *Insulation and Refractories*.

[6] Kam Chee Chook and Ai Hui Tan. Identification of an electric resistance furnace. *IEEE Transactions on Instrumentation and Measurement*, 56(6):2262–2270, 2007.

[7] Jinwu Kang and Yiming Rong. Modeling and simulation of load heating in heat treatment furnaces. *Journal of materials processing technology*, 174(1-3):109–114, 2006.

[8] J Kang, YK Rong, and W Wang. Numerical simulation of heat transfer in loaded heat treatment furnaces. 120:545–553, 2004.

[9] PS Grinchuk. Mathematical modeling of thermal operating regimes of electric resistance furnaces. *Journal of Engineering Physics and Thermophysics*, 83(1):30–40, 2010.

[10] Zhenglong Fu, Xinhong Yu, Huaili Shang, Zhenzhen Wang, and Zhiyuan Zhang. A new modelling method for superalloy heating in resistance furnace using fluent. *International Journal of Heat and Mass Transfer*, 128:679–687, 2019.

[11] G Colomer, M Costa, R Consul, and A Oliva. Three-dimensional numerical simulation of convection and radiation in a differentially heated cavity using the discrete ordinates method. *International Journal of Heat and Mass Transfer*, 47(2):257–269, 2004.

[12] A Gołdasz and Z Malinowski. Identification of the heat transfer coefficient at the charge surface heated on the chamber furnace. *Archives of Metallurgy and Materials*, 62, 2017.

[13] D Mariños, S Rojas, J Amaro, J Carvalho, A Mendiburu, and R Chucuya. Reheating furnaces in the steel industry: reduction of heat transfer losses by analyzing the types of insulation materials and thickness in each layer. 2020.

[14] Borislav Dimitrov, Hristofor Tahrilov, and Georgi Nikolov. Study and analysis of optimization approaches for insulation of an industrial grade furnace with electrical resistance heaters. 2012.