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Performance Analysis and Improvement of Existing Electric Resistance Furnace for Ceramic Sector in Thimi, Bhaktapur

Nitish Shakya [a], Bijendra Prajapati [b], Prajwal Raj Shakya [a]

[a] *Department of Automobile and Mechanical Engineering, Thapathali Campus, IOE, Tribhuvan University, Kathmandu, Nepal*
[b] *Department of Mechanical and Aerospace Engineering, Pulchowk Campus, IOE, Tribhuvan University, Lalitpur, Nepal*
[a] shakyanitish578@gmail.com, [b] bijendra.prajapati@pcampus.edu.np, [a] prajwalrajshakya@gmail.com

Abstract

Ceramic products are broad names for things made of clay. Thimi in the Bhaktapur district is one of the principal locations for industries which make ceramic products. Earlier, the ceramists of Bhaktapur used to depend in furnaces which used kerosene as an energy source to make ceramic products. Due to high price of kerosene, non-uniform distribution of temperature, eco-unfriendly and unavailability of large space to install furnace, such type of conventional furnaces are replaced by electric resistance furnaces (ERF). As the previous study has not been made to utilize such ERF to its full potential, it is chosen for study. The objective of this study is to analyze the performance and improve existing ERF of Thimi, Bhaktapur. Experimental based performance analysis is done by recording the temperature distribution and calculating the specific energy consumption, efficiency, and heat losses from the outer surface through radiation and convection. Based on the performance analysis, improvement of electric resistance furnace is done by constructing additional insulating wall of fire brick in the existing furnace. The result obtained from experiment was validated by using ANSYS 2022 R1. Based on the assessment, Everest pottery furnace was found efficient than Gathaghar pottery furnace with efficiency 37.32% and 32.11% for first and second firing respectively. Further, after modification of Everest pottery furnace, the furnace efficiency was improved by 18.89% and 15.51% for first and second firing respectively.

Keywords

Electric resistance furnace, Ceramics, Ansys 2022 R1, Performance analysis, Improvement,Specific energy consumption

1. Introduction

Thimi is known as Nepal's ceramic production hub. The ceramic products made in Bhaktapur are delivered in local as well international market. Ceramic products include different items like plate, cup, and other decoration materials and gift items.

Ceramics are regarded as one of humanity's finest and earliest and most useful creations. In part because they demonstrate how people first discovered how to manage fire and work with clay[1]. In terms of economic activity, artistic worth, and cultural legacy, ceramic production plays a significant role all over the world[2]. Inorganic solids that are not metallic are referred to as ceramics[3]. Ceramics, on the other hand, are a solid made by firing inorganic particles[4]. Extended service life, low density, corrosion resistance, non-toxicity and chemical inertness, high strength and resistance to heat and fire are some of the key characteristics of ceramic products[5, 6, 7]. These characteristics make ceramics a better material than metal for a variety of applications[8].

Ceramic goods are produced in a mostly uniform manner. Typically, raw materials are cast, blended, extruded, or formed by pressing. Water is frequently used in the manufacturing process for thorough out mixing and shaping. Dryers are used to evaporate the water used in this procedure. After that, the items are either manually inserted into the kiln or put on carriages that move materials through continuously operating kilns[3].

Bisque fire is the first firing of objects to temperatures ranging from 800-950 °C. The goal of this fire is to make the items sturdy enough to handle without difficulty while glazing. The bisque-fired body of the object is porous and absorbs water from the glaze, causing the glaze to cling to the surface. During glaze firing, objects are heated to the temperature required to melt the glaze. At the same time, the body is engineered to sinter as desired into a suitable object that is thick and long-lasting. Various clay types and glazes have different ultimate glazing temperatures[9].

In a variety of industrial manufacturing processes, electric furnaces are utilized for heating purposes. Where more precise temperature control is needed, electric furnaces are utilized. Depending on how heat is produced, there are three different types of electrical furnaces. They are induction heating furnaces, resistance heating furnaces and arc furnaces[10]. Resistance or induction heating are both possible in electric furnaces used for industrial process heating. Heating elements are used in resistance heating furnaces to produce heat in a heating chamber. Depending on the required temperature, Ni-chrome wire, Kanthal wire, or graphite rods are utilized as heating components. There are two types of resistance heating namely direct resistance heating and indirect resistance heating. In direct resistance heating, the substances that need to be heated are passed via the current. This method is used in a variety of common industrial equipment, welding, and boiler electrodes. A resistive element is used in indirect resistance heating process to generate heat, which is then transferred to the materials to be heated by convection or radiation[11]. Applications for this method include heaters and resistance furnaces. Resistance coil that encloses the object to be heated receives a current during induction heating. The mass of the object to be heated determines the appropriate electric current frequency[12].

Previously, people of Bhaktapur used furnaces which were operated by kerosene as a source of energy. As the price of kerosene was high, it was becoming uneconomical for ceramic product production. Eco-unfriendly, required large space to install, unequal distribution of temperature in the furnace walls were the reasons today ceramists of Bhaktapur are shifting towards ERF. Electricity is cheap, eco-friendly and electric furnaces do not require large space to install, electric furnaces are becoming popular in ceramic industry. Glazed pottery is obtained after completing two firing stages i.e., first firing and second firing. The first firing is done when the clay is given proper shape and dried in the sun whereas the second firing is done after glazing the pottery obtained after the first firing. A high temperature is required to complete the process.The ERF works at high temperatures so insulating materials and refractory bricks play a vital role to confine the heat inside the furnace. Good quality refractory brick and insulating material prevent the loss of heat to the surrounding through convection and radiations. Minimum loss of heat from the outer surface of the furnace helps to improve the efficiency of the furnace.

2. Methods and Methodology

2.1 Data Collection

Based on location, design and firing procedure, two sites are selected i.e., Everest Pottery Furnace and Gathaghar Pottery Furnace for data collection.

2.2 Case Study 1: Everest Pottery Furnace

In this site, first firing of ceramic object weighing 90.72 kg is done which consumed 82.42 kWh electricity. The first firing cycle took 430 min to complete and final temperature recorded was 895°C. After glazing, second firing of glazed object weighing 100.8 kg is done which consumed 132.25 kWh electricity. The second firing cycle took 690 min to complete and final temperature recorded was 1125°C. During both process the inside and outer wall furnace temperatures is recorded.

Figure 1: Everest pottery furnace

Figure 2 shows that temperature of object is rising slowly till it reaches 283°C because during this period furnace door is kept slightly open about 1 inch and among three heating coils only two heating coils are operated until 10:00 AM. In this duration, the moisture present in object takes latent heat and gets vaporized as well as the object temperature increases gradually taking sensible heat. After 10:00 AM the door is closed, then all three coils are operated which increases the temperature significantly. At the temperature 400 to 650°C, the crystal water is eliminated. Finally, at 3:10 PM the temperature reaches 895°C and first firing is completed.

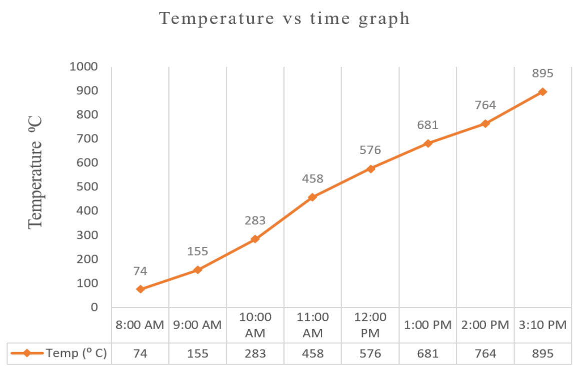


Figure 2: Inside temperature variation in the furnace chamber at the Everest site (First firing)

Figure **3** shows the temperature profile during second firing, the graph shows the significant rise in temperature from beginning which heats the object and helps to melt the glaze however, the high rate of temperature increment, may shrink the object unevenly creating cracks in the object.

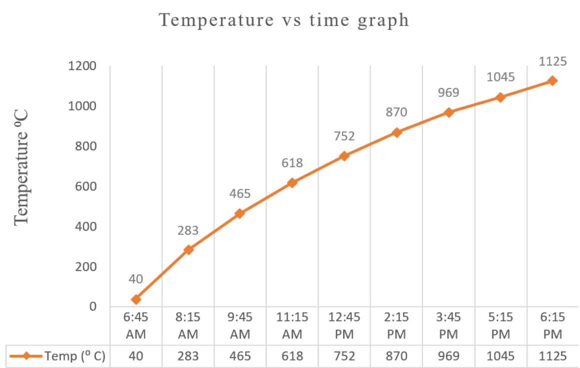


Figure 3: Inside temperature variation in the furnace chamber at the Everest site (Second firing)

Figure **4** illustrates that the temperature distribution in the furnace's front and side walls is similar, however the temperature distribution in the top cover is below the front and side wall because the heating elements at top zone are not operated during initial firing.

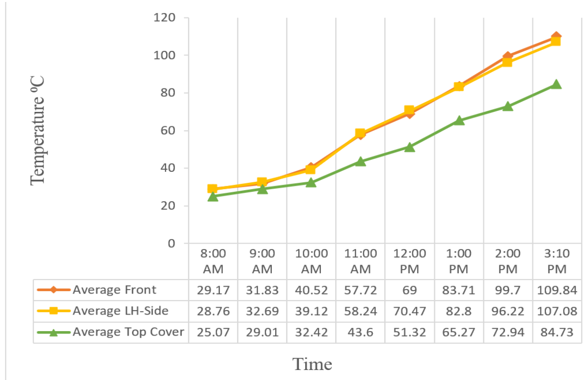


Figure 4: Temperature variation on furnace wall at Everest site (First firing)

Figure **5** depicts at 6:15 PM, the maximum temperature reaches to 136.64°C at the top cover. Similarly, at the front and side wall, temperature reaches to 126.16 °C and 111.7°C respectively. During second firing, three coils are operated due to which concentration of heat is high whereas the absence of refractory brick in top cover makes it difficult to prevent the heat loss from top cover. The front wall and side wall consists of refractory brick along with ceramic fiber blankets but these blankets are not in good condition which creates the non-uniform distribution of temperature in these walls.

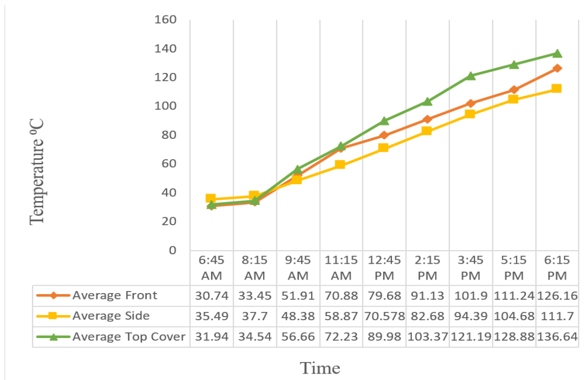


Figure 5: Temperature variations on the furnace walls at the Everest site (Second firing)

2.3 Case two: Gathaghar pottery Furnace

At this location, a ceramic object weighing 86.79 kg underwent its first fire, consuming 93 kWh of electricity. The duration of the first firing cycle was 465 min, and the maximum temperature that was measured was 898°C. After glazing, a second firing of the 96.36 kg, glazed product is completed, using 141 kWh of electricity. The final temperature measured during the second firing cycle, which lasted 705 min, was 1130°C. The temperatures of the inner furnace chamber and outer walls are measured during both processes.

Figure 6: Gathaghar pottery furnace

As can be seen in Figure **7**, the temperature of the object gradually increases until it reaches 240°C since the furnace door is left open by about 1 inch throughout this time, and only two of the three heating coils are used until 11:30 AM. During this time, the object's moisture absorbs latent heat, vaporizes, and progressively increases temperature due to sensible heat. The door is shut after 11:30 AM, and all three coils are then turned on, greatly raising the temperature. The crystal water is destroyed at temperatures between 360°C and 565°C. Finally, at 5:15 PM, the first firing is finished and the temperature hits 898°C.

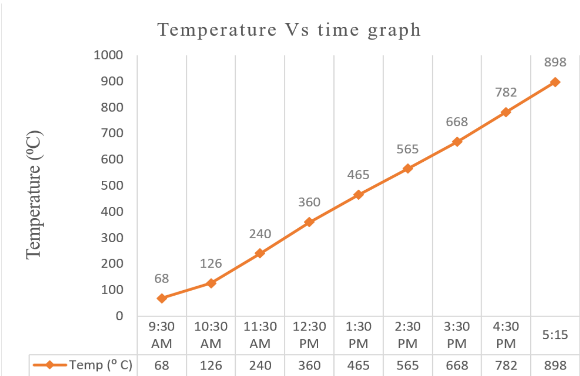


Figure 7: Inside temperature variations in the Gathaghar furnace chamber (First firing)

Figure **8** indicates inside temperature graph of second firing cycle. This graph trend demonstrates that the firing begins slowly and gradually rises until it reaches 225°C. Then it increases significantly till it attains 1130°C. This characteristic curve demonstrates the need for ceramic heating.

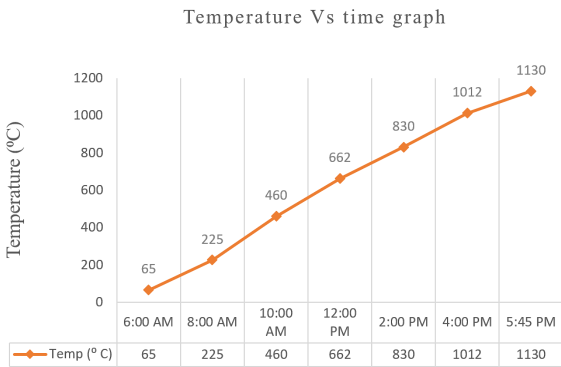


Figure 8: Inside temperature variations in the Gathaghar furnace chamber (Second firing)

Temperature distribution curve (Figure **9**) shows that maximum temperature reaches at side wall which is about 152°C and minimum temperature reaches at top cover with 115.5°C.

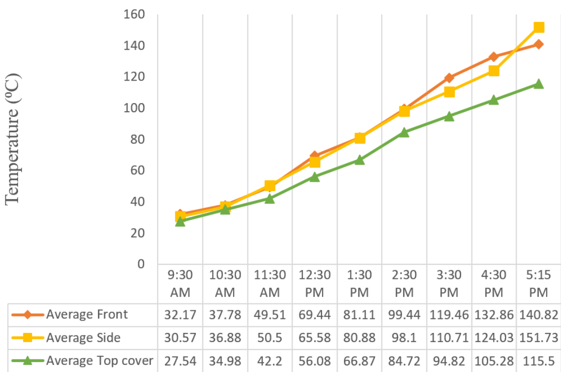
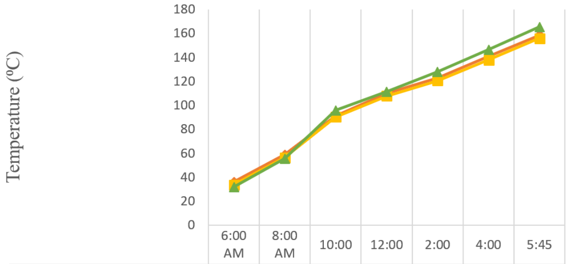


Figure 9: Temperature variation on wall of furnaces at Gathaghar site (First firing)

Figure **10** illustrates the temperature profiles of furnace walls do not vary significantly but the temperature developed at the outer walls are higher comparison to Everest pottery furnace with maximum temperature reaching to 165.42°C at top cover. Hence, it indicates the poor insulation in Gathaghar pottery furnace.

2.4 Comparative Performance indicators of ERF

Table **1** shows the performance comparison between Everest pottery furnace, Gathaghar pottery furnace and Modified Everest pottery furnace based on firing time,



	6:00 AM	8:00 AM	10:00	12:00	2:00	4:00	5:45
Average Front Temperature	36.11	58.86	91.39	110.02	122.79	140.83	158.61
Average Side Temperature	33.73	56.39	90.36	107.79	120.61	138.01	155.92
Average Top cover Temperature	31.94	55.43	95.87	111.48	127.97	146.54	165.42

Figure 10: Temperature variations on the furnace walls at the Gathaghar site (Second firing)

maximum temperature, efficiency, specific electricity consumption and heat loss(convection and radiation).

3. Design and modelling

3.1 Dimensional model for steady thermal analysis

Since the furnace of Everest pottery is more effective than that of Gathaghar pottery, it will be taken into consideration for the modification of heat resisting walls. During modification of existing Everest furnace the additional wall of fire brick of thickness 11.5 cm is added. According to collected data, the front wall's dimensions, thickness of refractory brick and fiber blanket of modified Everest furnace are shown in Figure **11** (All dimensions are in cm).

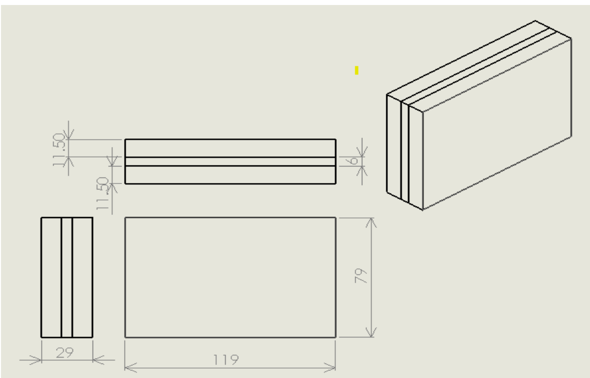


Figure 11: Front wall design (orthographic) in solid works

3.2 Boundary conditions

Based on experimental results, the boundary condition at wall boundaries was determined. Heating coil temperature for first and second firing was given as 1163K (890°C) and 1391K (1118°C) respectively. The ambient temperature is taken as 297K (24°C) and convective boundary condition on outer wall with heat transfer coefficient of 6 W/m^2K.

3.3 Mesh generation

With adaptive scaling and a resolution of 5, the furnace's meshing produced 79336 nodes and 16211 elements. The steady state thermal simulation is carried out following the generation of this mesh which is shown in Figure **12**.

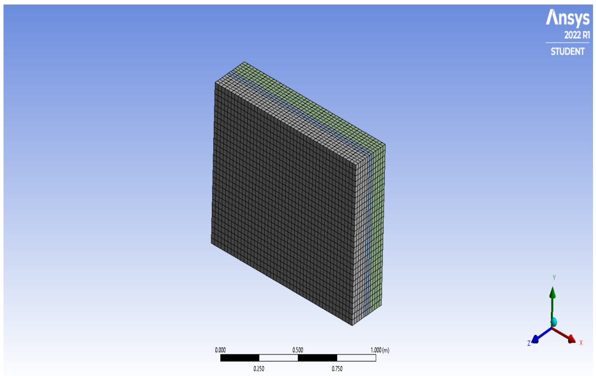


Figure 12: Meshing for the steady state thermal analysis (Modified Everest pottery furnace)

4. Modification and improvement

4.1 Modification of existing furnace

Figure **13** represents the modified existing furnace which was done with the prime objective of decreasing the heat losses due to convection and radiations from furnace walls.

4.1.1 Construction

The energy losses from the wall depends upon emissivity of walls, conductivity of refractories. So, the proper selection of insulating brick was necessary to minimize the heat loss. With thermal conductivity 0.48 W/m. K, emissivity 0.75 and density 7.05 kg/m3 fire clay brick with dimension 22.9 cm x 11.5 cm x 7.6 cm was selected. Because of low density and thermal mass of fire brick, the energy loss due to heat storage by additional fire brick wall was assumed to

Table 1: Comparative performance indicators

Description	Everest site	Gathaghar site	Modified Everest Furnace
First firing			
Maximum temperature recorded (°C)	895	898	890
Average Front wall temperature (°C)	109.84	140.82	87.88
Firing time (min)	430	465	355
Specific energy consumption (First firing),kWh/kg	0.908	1.071	0.755
Efficiency First firing (%)	37.32	31.78	44.37
Direct radiation heat lost from outer surface (MJ)	4.88E-01	1.75E+00	2.61E-01
Direct convection heat lost from outer surface (MJ)	5.18E+01	8.98E+01	4.14E+01
Second firing			
Maximum temperature recorded (°C)	1125	1130	1118
Average Front wall temperature (°C)	126.16	158.61	103.52
Firing time (min)	690	705	590
Specific energy consumption (Second firing),kWh/kg	1.312	1.463	1.117
Efficiency Second firing (%)	32.11	28.09	37.09
Direct radiation heat lost from outer surface (MJ)	2.69E+00	4.44E+00	1.67E+00
Direct convection heat lost from outer surface (MJ)	1.08E+02	1.63E+02	8.27E+01

be minimum. The fire brick lining was placed over the walls after installing new ceramic fiber blanket. To bind the fire bricks and to plaster the outer cover the mixer of ash, ceramic cement was used as it acts as insulation. Finally composite wall was created with additional width of 11.5 cm. In addition, hole with diameter 6 cm at the height of 63.5 cm from the bottom of furnace was drilled.

Figure 13: Everest Pottery furnace after modification

4.2 Improvement

Experiment on modified Everest pottery furnace was performed and the outer wall temperature of the modified furnace was found to be decreased compared to original Everest pottery furnace. Details of improvement are mentioned in below Table 2.

5. Result and discussion

5.1 Efficiency

Figure 14 represents efficiency of Everest pottery furnace is better than Gathaghar however, when the Everest pottery furnace was modified by adding insulating wall the efficiency of Everest pottery furnace was improved by 18.89% (first firing) and 15.51% (second firing). The efficiency of modified furnace during first firing and second firing was obtained as 44.37% and 37.09% respectively which is better than that of original Everest pottery furnace.

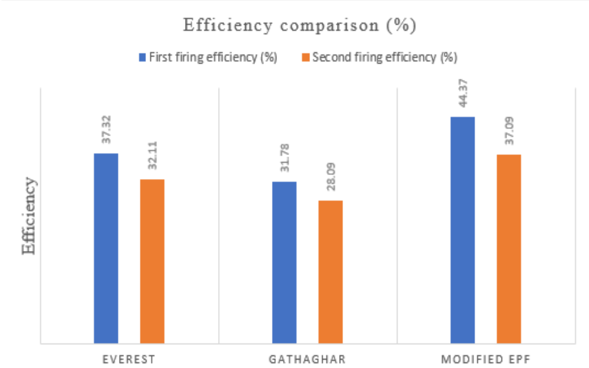


Figure 14: Efficiency

Table 2: Improvements after modification of existing Everest pottery furnace

Description	Everest furnace	Modified furnace	Difference	Improvement
Front wall temperature				
First firing (°C)	109.84	87.88	21.96	19.99 % decrement
Second firing (°C)	126.16	103.52	22.64	17.94 % decrement
Heat loss (Radiation)				
First firing (MJ)	4.88E-01	2.61E-01	0.227	46.51 % decrement
Second firing (MJ)	2.69E+00	1.67E+00	1.02	37.91 % decrement
Heat loss (Convection)				
First firing (MJ)	5.18E+01	4.14E+01	10.4	20 % decrement
Second firing (MJ)	1.08E+02	8.27E+01	25.3	23 % decrement
Efficiency				
First firing (%)	37.32	44.37	7.05	18.89 % increment
Second firing (%)	32.11	37.09	4.98	15.51 % increment
Specific energy consumption				
First firing (kWh/kg)	0.908	0.755	0.153	16.85 % decrement
Second firing (kWh/kg)	1.312	1.117	0.195	14.86 % decrement

5.2 Specific energy consumption

Figure 15 indicates that highest electricity consumption to fire one kg of ceramic is of Gathaghar site whereas lowest consumption is of modified furnace of Everest site. The specific energy consumption was found to be improved by 16.85% (first firing) and 14.86% (second firing) when compared to existing Everest pottery furnace.

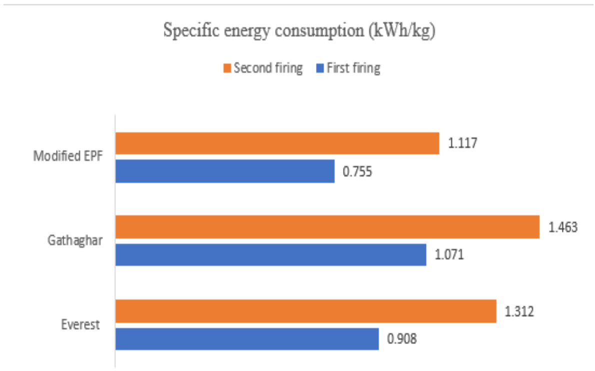


Figure 15: Specific energy consumption

5.3 Convection and radiation heat loss

Heat loss in atmosphere through radiation and convection is found to be high in Gathaghar compared to Everest pottery. After modifying the furnace linings, the heat loss due to radiation and convection decreased by 46.21% and 20% respectively during first firing and similarly by 37.91% (radiation) and 23% (convection) for second firing compared to Everest pottery furnace before modification.

5.4 Steady thermal analysis

Steady state thermal analysis of Everest pottery furnace was performed in Ansys 2022 R1 student version by providing real operating parameters as a boundary condition.

Figure 16 shows the steady thermal analysis of front wall of modified Everest pottery furnace for first firing it was observed that the front's outer wall's temperature was 77.97°C. (350.97K). The actual temperature reached was 87.88°C, hence the approximate difference between simulation and experiment result was found to be 12.71%.

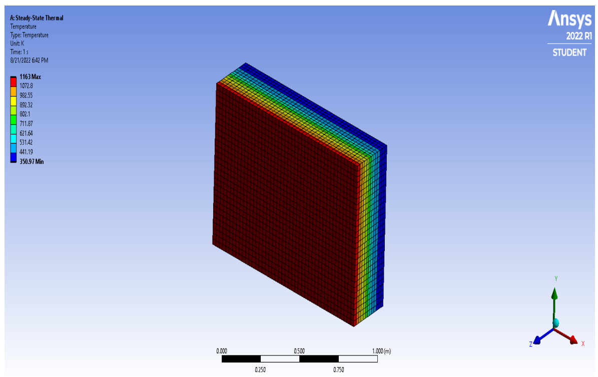


Figure 16: Steady thermal analysis of front wall (Modified Everest pottery furnace) for first firing

The outer wall (front) temperature was determined to be 90.42°C (363.42K) when the simulation was completed as shown in Figure 17 . It was recognized that there was a 14.49% error between the simulation and experimental data (the actual temperature was

103.52°C).

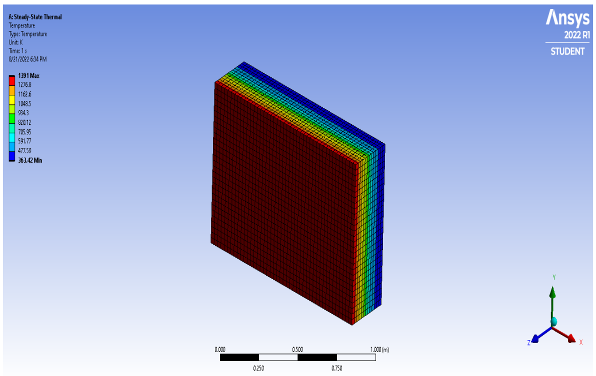


Figure 17: Steady thermal analysis of front wall (Modified Everest pottery furnace) for second firing

6. Conclusion

This study was aimed to analyze the performance and to improve the ERF present in Thimi, Bhaktapur. Performance analysis was done by collecting temperature data of inside chamber and outer walls of furnaces and improvement was done by adding insulating wall of fire brick. This paper principally focused to compare the ERF based on their efficiency, specific energy consumption and heat loss. It is found that the Everest pottery furnace is more efficient than Gathaghar pottery furnace. Further, Everest pottery furnace was modified by adding insulating fire brick and experiment was conducted which showed the decrease in outer wall temperature. Hence, this paper concludes that addition of insulating wall decreases the heat loss through convection and radiation from outer walls and thus increase efficiency of the furnace.

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