

Thermal Investigation of an Indirectly Heated Rotary Kiln

T. F. Mokoena¹, M.D Madyira¹, T.O Babarinde^{1,3}, S. A Akinlabi¹

¹Department of Mechanical Engineering Science, University of Johannesburg, South Africa

²Department of Mechanical & Industrial Engineering Technology, University of Johannesburg, South Africa

³Mechanical Engineering Department, Covenant University Ota, Nigeria

E-mail address: taiwo.babarinde79@gmail.com, stephenakinlabi@gmail.com, dmadyira@uj.ac.

Abstract. Rotary kilns are very important to the construction industry and many others. These machines are very inefficient, and this is a big concern since they rely on fossil fuels to operate. The aim of this research is to use the power of computational fluid dynamics to save costs and time to optimize the indirectly heated rotary kiln. The research will mainly focus on the thermal analysis of the rotary kiln. The significance of this research mainly lies in the ever-growing need to preserve natural resources and in this case, it is by optimizing highly inefficient machinery such as rotary kilns. The numerical model study was conducted using steady state conditions and was also validated. It was found that the numerical model results deviated from experimental results by 10.63%. The optimization process was conducted where the mass flow rate of the air was varied and while the fuel flow rate was kept constant. The reverse was done where the mass flow rate of fuel was varied while the flow rate of air was kept constant. It was concluded that there exists an inverse relationship between the increase of the flow rate of air and the temperature distribution and there exists a directly proportional relationship between the increase of fuel flow rate and the temperature distribution.

Keywords: Rotary Kiln, Optimization, CFD

1. Introduction

Fossil fuels play a very significant role in modern society and continue to do so because of their versatile nature. These precious commodities prove to be the most convenient way of transforming one form of energy to another and more specifically, chemical energy to thermal energy. The need for thermal energy has grown significantly due to power generation and thermal processing to name a few. Thermal processing is defined as the application of heat to bring about a certain chemical and physical change to material [1]. There are numerous ways in which thermal processing can be executed and a rotary kiln is one of them. Rotary kilns are long rotating drums that are used for thermal processing of certain materials over a specified amount of time [2]. These machines use fossil fuels such as natural gas as their source of fuel for thermal processing. They do however come with big challenges such as dust emissions and high thermal inefficiency [3]. It is therefore, important that the process in rotary kilns is carefully studied and from any results obtained, recommendations can be made to future designs to make them more efficient and ultimately use natural resources such as fossil fuels sparingly. Most conventional rotary kilns use fossil fuels as a source of energy to carry out their processes. However, due to their high poor thermal efficiency and their reliance on the price of fossil fuels, there is a need to make them more efficient so that more work can be done with less energy supplied to the kiln.

A rotary kiln is a device that is used in pyro processing to raise temperatures of material in a continuous process [4]. Due to the development and evolution of rotary kilns, they have had synonyms such as cement kilns and lime kilns [4]. Rotary kilns are devices that are used to process materials at high temperatures to create a chemical change or physical change to the heated material [5]. These days, rotary kilns have acquired various applications such as reduction of oxide ore, reclamation of hydrated lime, calcining of petroleum coke, hazardous waste reclamation, and others. Rotary kilns can operate at temperatures above 2000K with the aid of natural gas as a fuel source [1]. Rotary kilns are slightly tilted and at an angle and rotate at a controlled rate by a motor. They are tilted at an angle so that they material can be extracted with



the aid of gravity and the kiln is rotated so that the material which is being processed can be consistent in terms uniformity. An industrial rotary kiln usually has a diameter of 2-2.5m and a length of 50-80m [3]. These machines, however, come with a number of problems. They have poor thermal performance; they create a lot of dust and have a certain amount of inconsistency in the uniformity of the products that they produce [4]. The issue of inconsistency in the uniformity of the products that are processed has influenced the design of the interior of the kilns and the speed at which the kiln is rotating which will be further discussed in the bed phenomenon of the kiln. There are many types of kilns in the rotary kiln practice namely: long dry kilns, short dry kilns and indirectly fired rotary kilns. The long dry kiln shares a common trait with the wet kiln and that is the fact that the preheating, drying and calcination all occurs in one vessel. They normally operate well when the feed particles are large. Applications include lime kilns and lightweight aggregate kilns where the mined stones are crushed to about 1.3–5cm before feeding them into the kiln [4]. Short dry kilns are usually accompanied by an external preheater or pre-calciner in which the feed is dried, preheated, or even partially calcined prior to entering the main reactor. Short dry kilns normally have feed material which is almost calcined.

The applications are mostly in cement and lime processing [7]. Indirectly heated rotary kilns take a different approach to the way in which they are heated compared to the directly heated kilns. These types of kilns are designed this way for the case where direct contact between the material of the gas or heat source and the material which is being processed is undesirable. These kilns are relatively small due to their low efficiency and are used for applications of calcinating specialty materials. Indirectly fired rotary kilns have multiple and compartmentalized temperature-controlled zones which can be electrically or gas heated separately [4]. Sass [8] developed a computer a modelling using empirical relationship for heat transfer radiation in a rotary kiln. Ghoshdastidar et al. [9] also carried out simulation results on an improved heat transfer model for a rotary kiln that is being used for preheating and drying of wet iron ore. Schmidt and Nikrityuk [10] developed a 2D numerical simulation model of a transient temperature distribution by granular mixing in a horizontal rotary kiln. Cundy [11] investigated an analytical model between the solid in a rotary kiln and heated wall of a rotary cylinder with initial moisture content of 2-7% of mass of the dry the solids. . Ghoshdastidar and Unni [12] also developed a simulation model based on steady state heat transfer of drying and pre-of moisture solids in the non-reacting zone of a cement rotary kiln. In another study, Ghoshdastidar and Agarwal [13] carried out a numerical simulation study of heat transfer in a rotary kiln that was being used for drying and preheating of wood chips with superheated steam. Due to growing need for solid natural resources there is need for energy management and energy efficiency system. This research presents a steady state thermal analysis of a rotary kiln and develops a numerical model for optimization of the thermal performance of the rotary kiln system.

The aim of the project is to develop a numerical model that will characterize the thermal performance of an indirectly heated rotary kiln with acceptable accuracy using computational fluid dynamics and use the results from the numerical model to optimize the rotary kiln.

2. Results and discussion

The experimental results obtained from the data logger are from the various locations of the thermocouples. The results are summarized in graphical form in Figure 1.

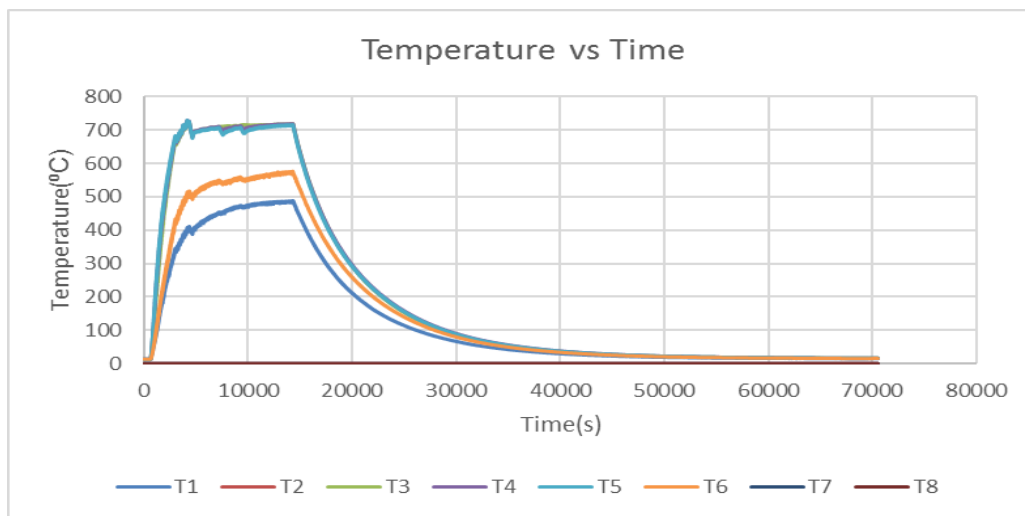


Fig.1 Experimental result of variation of temperature of the kiln with time

The graph is plotted with temperature as a function of time in seconds. The experiment was run over a course of 1 day. Since the temperatures of the different thermocouples are a function of time, it can be concluded that the results are transient. Initially, the kiln was at a temperature of 11°C due to the surrounding environment. When the burner is switched on, the temperature measured by the different thermocouples rises sharply due to high temperature difference. As the time progresses to approximately 3000 seconds, the temperature at each location starts to stabilize. This is due to the fact that the burner has reached the maximum amount of power it can give out and therefore, it can be assumed that the kiln was at steady state at this point. After 15000 seconds, the power supply from the burners was cut off and the kiln was allowed to cool down. The CFD model was run under steady state conditions and therefore the most crucial results were at the time where the temperatures do not vary significantly with time. These temperatures, along with their locations on the kiln are important and were used to validate the model. The highest temperature observed at each location was used. These results are summarized in Table 1.

Table 1: Temperatures at different locations

Location (mm)	355	850	1255	1760	2700
Temperature($^{\circ}\text{C}$)	478.8	705.9	711.4	714.7	560

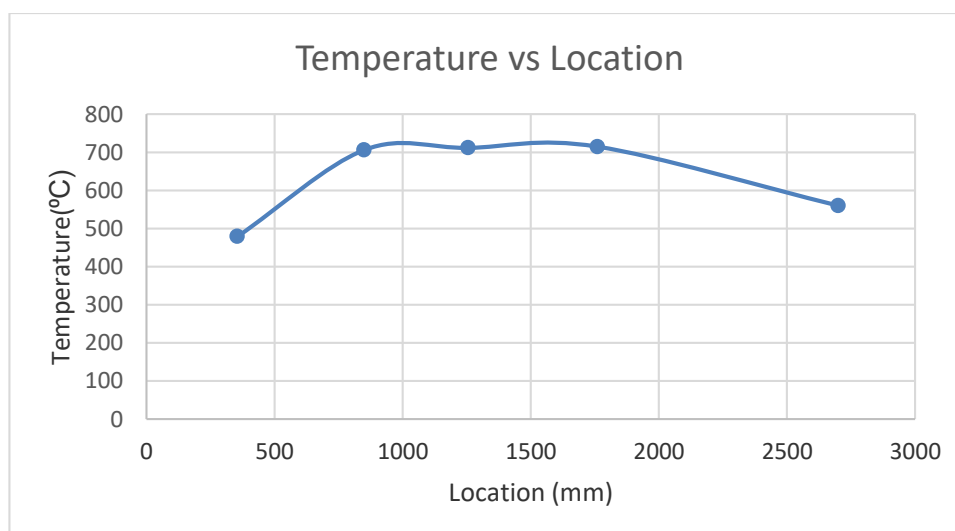


Fig 2 Experimental results at steady state conditions based on location

Computational fluid dynamics is a very complex tool which uses numerical analysis to produce results. This tool does this by creating a mesh which is applying cells to the part which is to be studied. The CFD software analyses the interaction between the cells based on the study which is being performed. The size of the cells can be easily changed to any desirable size. This in return changes the number of iterations done by the software based on the size of the mesh. This means that the smaller the cell sizes, the more computational effort required, and more iterations done by the computer. The inverse of this happens as the mesh size is increased. This however, has a very large impact on the accuracy of the results from the computations. The mesh sensitivity for the model was conducted by measuring the temperature at the exit point of the drum without changing any other conditions but the mesh size.

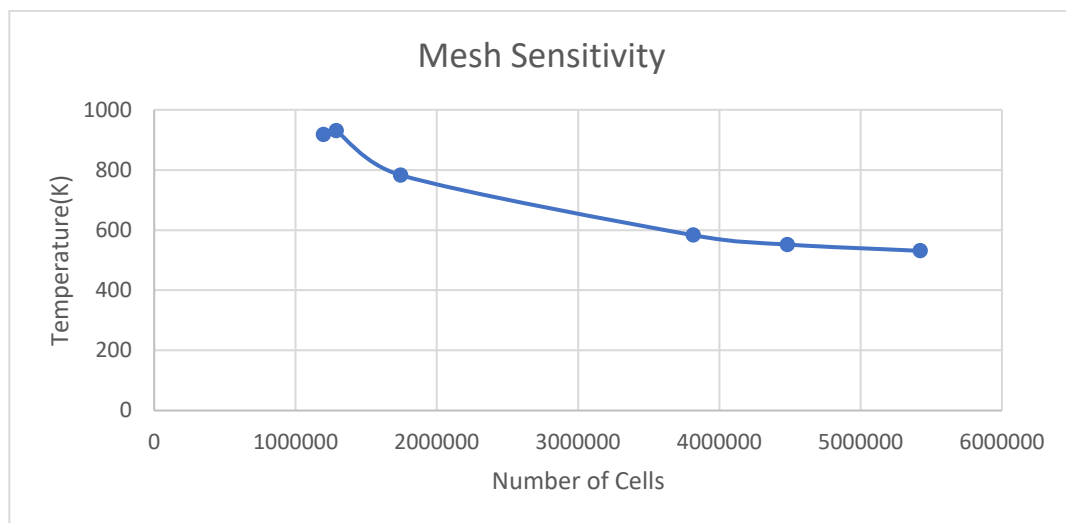


Fig. 3 Mesh sensitivity study

Table 2: The summary of the model boundary

Parameter	Value	Unit
Outside Walls Temperature	11	$^{\circ}\text{C}$
Ambient air convection coefficient	10	$\text{W/m}^2 \cdot \text{K}$
Mass flow rate of air	0.01	kg/s
Mass flow rate of fuel	4.11×10^{-4}	kg/s
Pressure	82.5	kPa
Initial air and fuel temperature	25	$^{\circ}\text{C}$

2.1 Model Validation

After the mesh sensitivity study was conducted, the boundary conditions were applied to the model and to see whether the model results correlate with the experimental results. The model results at the locations of interest are summarized in

Table 3. The results were further plotted in Fig and compared to those of the experimental results.

Table 3 Numerical model results and experimental results comparison

Location (mm)	355	850	1255	1760	2700
Temperature($^{\circ}\text{C}$) (Experimental)	478.8	705.9	711.4	714.7	560
Temperature($^{\circ}\text{C}$) Model	391.94	672	705	698	409
Error (%)	18.1	4.8	0.899	2.4	27
Average error (%)	10.63				

From the comparison at the different locations, it can be concluded that the average difference between the model results and the experimental results is 10.63%. The validation is illustrated in a graph.

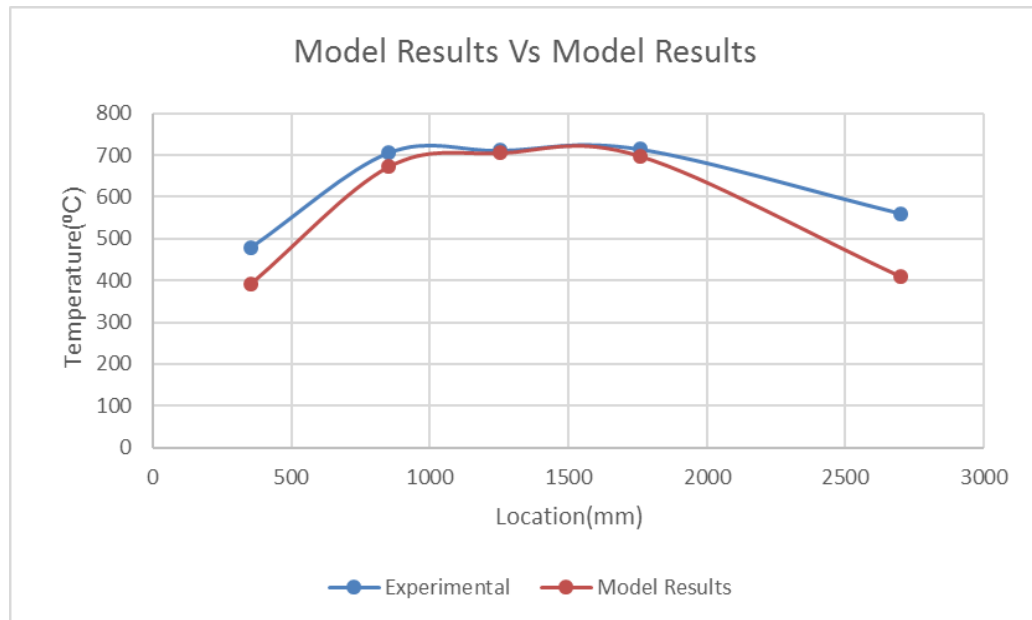


Fig. 4 Comparison of experimental result with model result

The flow field given by Figure 5 illustrates the flame and temperature distribution of the kiln. it can be observed that some of the thermal energy produced by the combustion of propane was used to heat up the insulation of the kiln. Though most of the energy was used to heat up the drum and the material in the drum.

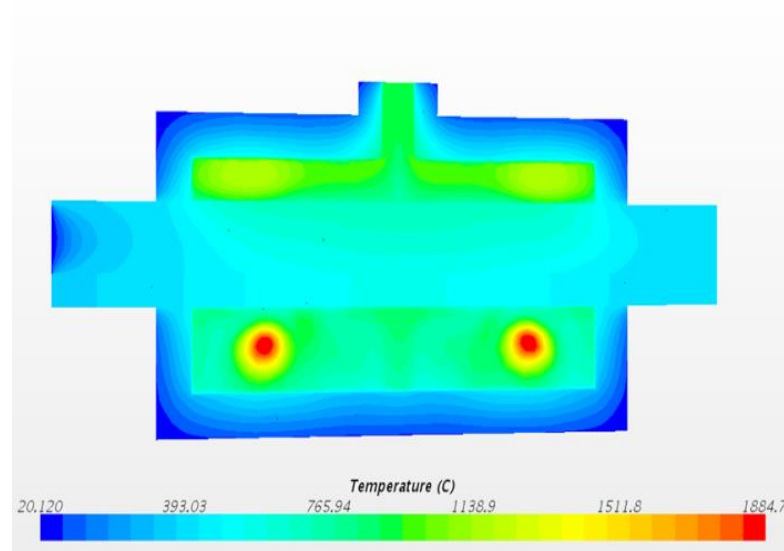


Fig. 5 Temperature distribution in the drum

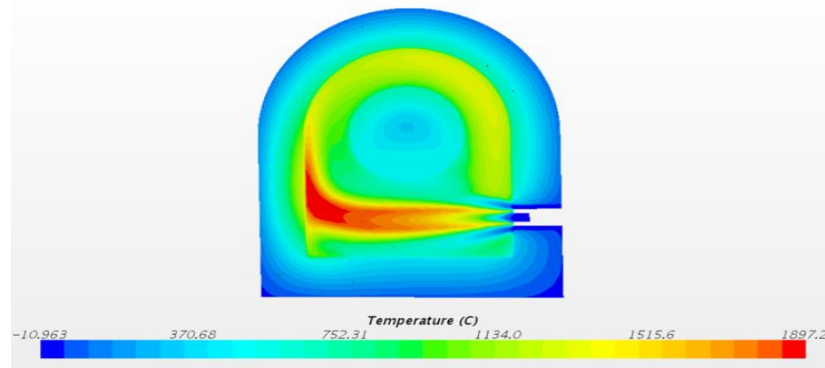


Fig. 6 Flame distribution from experimental boundary conditions

2.2 Model Optimization

The main aim of the experimental program was to analyze the changes that take place when the mass flowrate of the fuel is varied while the mass flowrate of the air is kept constant. The second part of the experimental program was to analyze the changes that take place when the mass flow rate of the air is varied while the mass flowrate of the fuel is kept constant. This was done on the model since it is very close proximity to the experimental results and thus the same would be observed if it was to be conducted in an experiment.

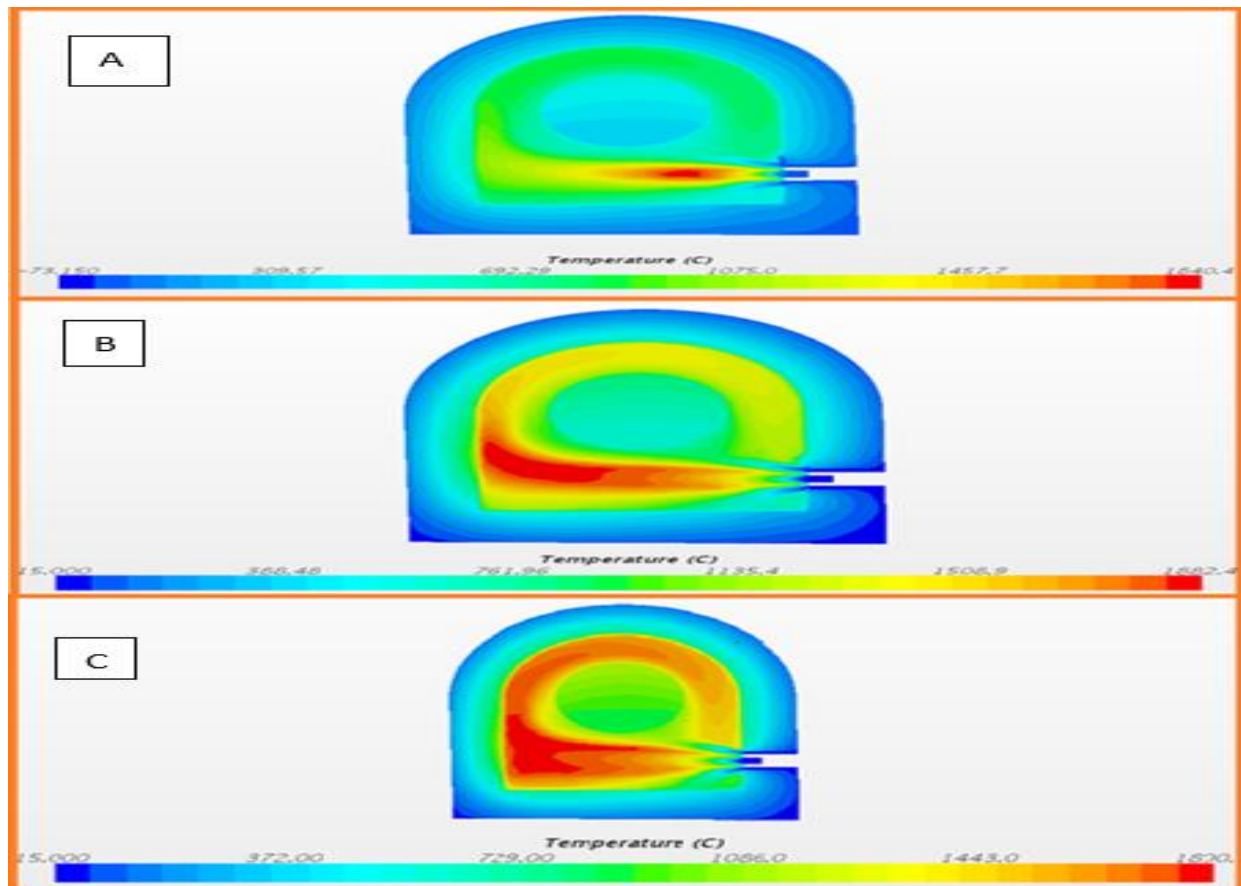


Fig. 7 Temperature distributions for fuel mass flow rates of (A) 3×10^{-4} kg/s, (B) 5×10^{-4} kg/s, (C) 6.5×10^{-4} kg/s

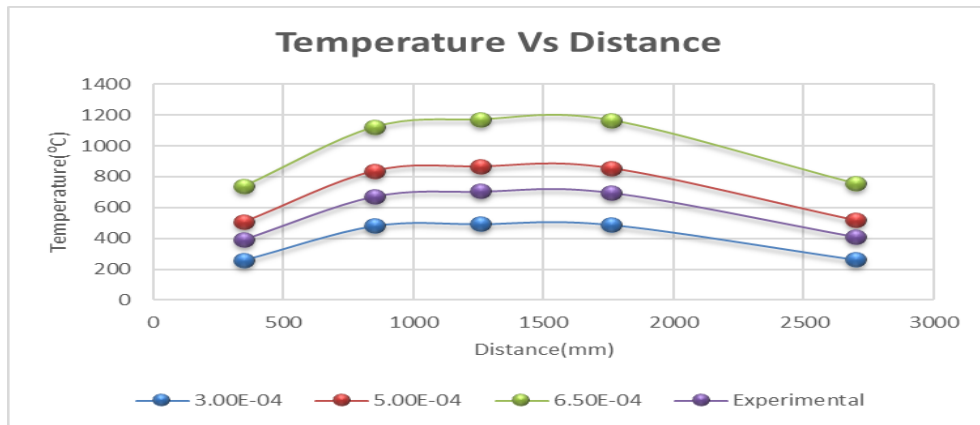


Fig. 8 Temperature distribution graphs along the kiln for fuel optimization

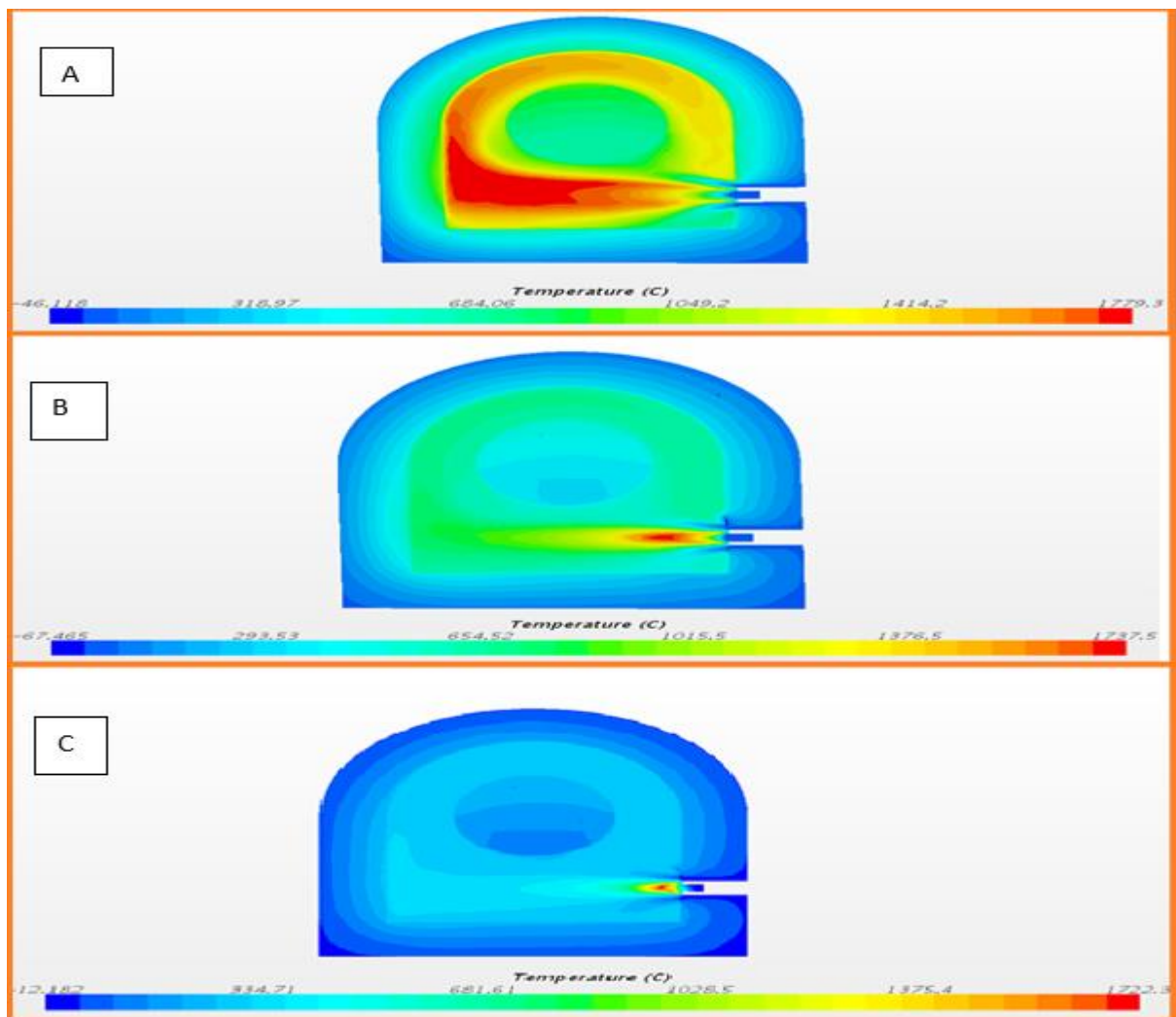


Fig. 9 Temperature distribution for air mass flow rate (A) 0.0075kg/s, (B) 0.03kg/s, (C) 0.05kg/s

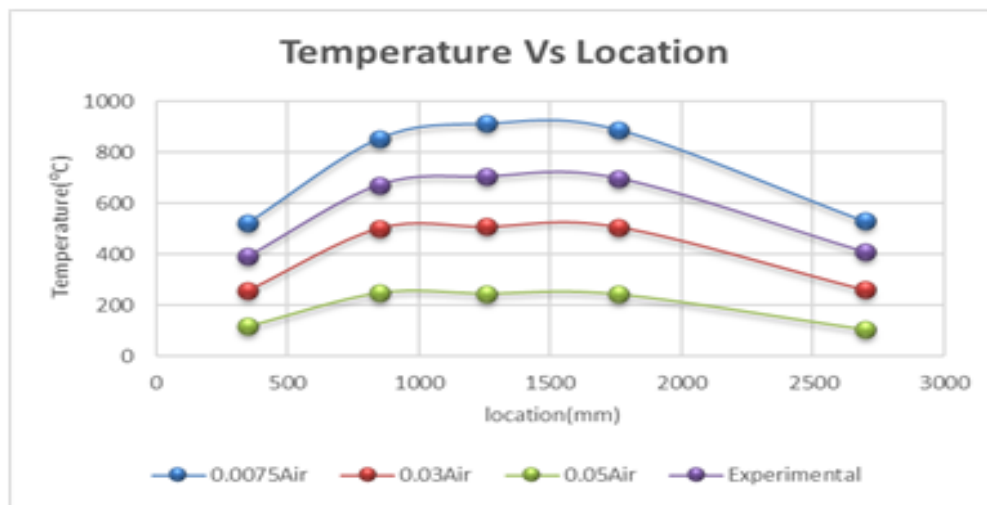


Fig. 10 Temperature distribution along the kiln length for air optimization

After the modelling process was complete, the validation of the model was conducted to see how close of an approximation the model is to the experimental results. The model was assumed to have been done at steady state conditions. This means that the validation of the model had to be done on using the steady state points from the experimental results. The average of 300 points from the experimental data was used to approximate the temperature at each of the five locations. These temperatures were used to validate the model results. It was found that the model results deviate from the experimental results by a magnitude of 10.63%. There are few factors that constituted to the error that was observed from the model results. The first and most important factor was the assumption of steady state conditions. This assumption means that the results are not extensively analysed as the kiln is in the process of heating up. The next factor that took part in the error of the results is the simplification of the model by not having the drum rotates during the heating process. This simplification meant that there will not be full mixing of the air during the heating process in the drum. The last factor that constituted to the error of the model was the choice of modelling the sand inside the drum as a solid component, even though it had the material properties of the sand. This factor contributed to the error at a larger scale than the other assumptions. This means that in the locations where the sand model is not in the section of the drum where the drum is in the combustion chamber, the temperature of those places will only rise due to the conductive nature of both the drum and the sand model. This was a problem because the material was not modelled as a flowing material.

The insulating layer of the kiln shell was also modelled. This was important because this part of the kiln has a big impact in the overall performance of the kiln. This is because any heat that is not lost to the environment due to both convection and conduction, will be supplied to the drum and thus making the kiln more efficient. However, the kiln insulation was not studied extensively during the experimental program.

From the optimization results, it can be seen that the overall temperature in the combustion chamber decreases as the mass flow rate of the air is increased while the mass flow rate of the air is kept constant. The temperature decreases because the overall flame from the burner decreases. The reverse happens when the mass flow rate of the air is kept at a constant while the mass flow rate of the fuel is increases.

From the optimization results, it can be seen that the overall temperature in the combustion chamber decreases as the mass flow rate of the air is increased while the mass flow rate of the air is kept constant. The temperature decreases because the overall flame from the burner decreases. The reverse happens when the mass flow rate of the air is kept at a constant while the mass flow rate of the fuel is increases.

3. Conclusion

The numerical model was found to have deviated from the experimental results by a magnitude of 10.63%. The reason for the error was discussed in the discussion section of the report. The main reason for

developing a numerical model was to save costs by running multiple tests on the numerical model without the cost of using fuel and raw materials. Since this numerical is within the acceptable range of similarity to the actual rotary kiln, this means that it can be used to vary certain parameters and to see what will happen and those occurrences will be observed on the actual rotary kiln. This process is known as the optimization. When the optimization was conducted, the mass flow rate of air was varied while the flow rate of the fuel was kept constant. When the mass flow rate of air was 0.0075kg/s, the highest temperature observed in the drum was 850°C. When the mass flow rate of air was 0.03kg/s, the highest temperature observed in the drum was 450°C. Lastly, when the mass flow air is 0.05kg/s the highest temperature observed in the drum is 220°C. It can be concluded that there is an inverse relationship between the air flow rate and the temperature distribution. When the mass flow rate of fuel is increased, there is a direct relationship with the temperature distribution.

References

- [1] Karl-Heinz, M. Roeb, P. Schwarzboezl and H. Warnecke, "Journal of Thermal Science and Thermal Applications," *Aluminium Remelting using solar heated rotary kilns*, vol. 123, no. 1, p. 8, 2001.
- [2] G. Handler, "FEECO International," FEECO International, 2017. [Online]. Available: <http://feeco.com/rotary-kilns/>. [Accessed 25 February 2017].
- [3] Z. Zhang and T. Wang, "Journal of Fluids Engineering," *Simulation Of Combustion and Thermal flow inside a petroleum coke rotary kiln*, vol. 2, no. 1, p. 12, 2010.
- [4] A. A. Boateng, *Rotary kilns-Transport Phenomena and*, New York: Butterworth-Heinemann, 2008.
- [5] FEECO International, "The rotary kiln hand book," 2015. [Online]. Available: <http://feeco.com/rotary-kilns/>. [Accessed 25 February 2017].
- [6] "SEW Gear Manufacturer," 2017. [Online]. Available: <http://www.sewgears.net/rotary-kiln-shell-manufacturer-in-india-new-delhi>. [Accessed 25 02 2017].
- [7] P. S. Ghoshdastidar, "Journal of Fluids Engineering," *Simulation and optimization of drying of wood and chip with superheated steam in a rotary kiln*, vol. 1, no. 1, p. 6, 2009.
- [8] A. Saas, Simulation of the heat transfer phenomenon in a rotary kiln, Ind. Eng.
- [9] P.S. Ghoshdastidar, G. Bhargava, R.P. Chhabra, Computer simulation of heat transfer during drying and preheating of wet iron ore in a rotary kiln, *Drying Technol.* 20 (1) (2002) 19–35
- [10] R. Schmidt, P.A. Nikrityuk, Numerical simulation of the transient temperature distribution inside moving particles, *Can. J. Chem. Eng.* 90 (2012) 246–262.
- [11] C.A. Cook, V.A. Cundy, Heat transfer between a rotating and a moist granular bed, *Int. J. Heat Mass Transfer* 38 (3) (1995) 419–432.
- [12] P.S. Ghoshdastidar, V.K. Anandan Unni, Heat transfer in the non-reacting zone of a cement rotary kiln, *J. Eng. Ind., Trans. ASME* 118 (1996) 169–172.
- [13] P.S. Ghoshdastidar, A. Agarwal, Simulation and optimization of drying of wood chips with superheated steam in a rotary kiln, *J. Therm. Sci. Eng. Appl., Trans. ASME* 1 (2009) 024501