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NUMERICAL ANALYSIS OF THE HEAT TRANSFER IN THE WALL OF ROTARY KILN USING FINITE ELEMENT METHOD ANSYS

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ABSTRACT

Heat transfer mechanism is complicated in case of rotary kiln as it includes conduction, convection and radiation at a same time. It is necessary to solve the governing heat transfer model numerically due to multi-dimensional nature of the model which takes in to account the thermal heat conduction in radial and circumferential direction. In order to predict and improve the evolution and the distribution of temperatures in the rotary furnace, a numerical analysis is undertaken using finite element package ANSYS. The standard element type plane 55 for two dimensional thermal solids is used. A numerical simulation includes temperature distribution on the internal surface of the wall in order to improve the understanding of the heat transfer process across it. Analysis of the temperature distribution across the circumferential and radial direction and the causes of temperature fluctuation due to the boundary conditions were studied thoroughly. There is a clear temperature distribution across the wall of the rotary kiln for various angular velocities, with different heat transfer coefficients and under different filling degree. Penetration depth, which is the region till where all curves meet together, has been easily observed on the radial side of the wall. Only this thickness takes part in heat transfer process. Penetration depth increases with increase in the filling degree. Temperature at the solid side decreases continuously and at the gas side it first increases because of the regenerative heat phenomenon. Experimental results are qualitatively matching with the numerical results. Temperature fluctuations increase with increase in rotational speed has also been observed.

NOMENCLATURE

α Heat transfer coefficient
p pressure
u velocity
λ thermal conductivity
T_W temperature of the wall

INTRODUCTION

Numerous heat transfer models for refractory kilns are available in the literature [1 2 3 4 5 6]. The heat transfer model from these previous works has to be solved numerically because of the two dimensional problems which consider the thermal heat conduction in radial and circumferential direction. Heat transfer mechanism is complicated in case of rotary kiln as it includes conduction, convection and radiation together. The first model for the prediction of the axial transport in a rotary cylinder was proposed by Sullivan in 1927 and then developed to study the isothermal transverse motion of a bed of particulate materials by Friedman and Marshall [7], Peary et al. [8]., Perron and Bui [9].

A mathematical model was described by Henein [10] to predict the conditions giving rise to the different forms of transverse bed motion in a rotary cylinder like slumping, rolling, slipping, cascading, cataracting, and centrifuging. Wu et al. [11] developed a 2D mathematical model based on the heat conduction mode in terms of the enthalpy formulation to simulate heat transfer and melting process in the scrap metals. A 3D steady-state model of a rotary calcining kiln was recently presented by Bui et al. [9]

Many researchers have different approach and the available mathematical models are not sound enough to describe the heat transfer between covered kiln wall and the particle in the bed. In general, a rotary kiln can be classified as internally heated and externally heated device. The heat transfer process in rotary kiln is complex; particularly a internally heated kiln. Fig. 1

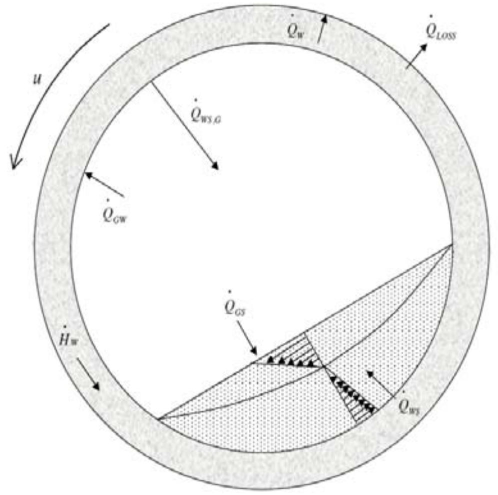

Figure 1: Modes of heat transfer in a rotary kiln

indicates mechanism of heat transfer in which radiation, convection and conduction all contribute together to the transfer of heat from gas to the wall and solid. At higher temperature in gases, radiation is the dominant heat transfer phenomenon [11]. The gas is a heat source which provides heat to the solids, as a heat sink, and the wall, as a regenerator. After receiving heat from the gas, the wall transmits it to the solid bed surface by radiation and to the underside of the bed by rotation and conduction. A portion of the heat is lost to the surroundings through its outer shell. Thermal stresses arise in materials when they are heated or cooled. Change in temperatures causes thermal effects on materials. Some of these thermal effects include thermal stress, strain, and deformation. The first effect we will consider is thermal deformation [10]. The purpose of this research paper is to build a model that simulates the temperature distribution in circumference and radial direction and to predict penetration depth. In order to predict and improve the evolution and the distribution of temperatures in the rotary furnace, a numerical analysis is undertaken using ANSYS finite element package.

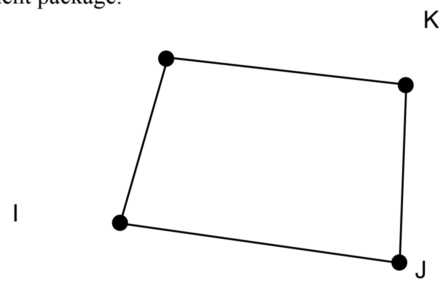

Figure 2: Plane 55 Elements

Figure 2 represents plane 55. It has four nodes with a single degree of freedom i.e. the temperature at each node. Rotating boundary conditions has been used to analyse the numerical simulation.

MODEL DESCRIPTION

The most famous equation for the steady state conditions is Fourier- Kirchhoff differential equation, it's in the from

$$c \cdot \rho \cdot \omega \cdot \frac{\partial T}{\partial \varphi} = \frac{\lambda}{r} \cdot \frac{\partial}{\partial r}\left(r \cdot \frac{\partial T}{\partial r} \right) + \frac{\lambda}{r^2} \frac{\partial^2 T}{\partial \varphi^2} \qquad (1)$$

polar coordinate, where φ is the angle of the circumference with respect to the center of the kiln and r is the radial coordinate, ω is the rotational frequency. Fig. 3 shows schematic of a rotary kiln and the symbol used for the modelling of heat transfer. It can reduces to two dimensional problems (φ, r) by neglecting axial thermal conduction along the kiln, as length of the rotary kiln is long enough in comparison with the diameter. This equation gives temperature distribution across the rotary kilns.

Two boundary conditions on the inner surface of the kiln set up in r and φ directions. Equation 2 represent heat transfer on the internal kiln wall in contact with the solid. $T_{r=Ri}$ is the inner surface temperature of the kiln wall. Mean temperature of the solid bed is represented by T_S. In this model we consider mean temperature of the bed so the transverse solid motion [17] and exact temperature distribution is not necessary.

$$-\lambda \left. \frac{\partial T}{\partial r} \right|_{r=Ri} = \alpha_{WS} \cdot \left(T_{r=Ri} - T_S \right) \qquad 0 \le \phi \le 2\varepsilon \qquad (2)$$

Solid region bound with the two times of the filling degree angle ε. The heat transfer in the contact region of gas and wall is mainly described with law of convection as linearization of the model is required.

$$-\lambda \left. \frac{\partial T}{\partial r} \right|_{r=Ri} = \alpha_{GW} . \left(T_{r=Ri} - T_G \right) \qquad 2\varepsilon \le \phi \le 2\pi \qquad (3)$$

$$\alpha_{GW} = \varepsilon_{eff} . \sigma . T_G^3 \left[1 + \frac{T_W}{T_G} + \left(\frac{T_W}{T_G} \right)^2 + \left(\frac{T_W}{T_G} \right)^3 \right] \qquad (4)$$

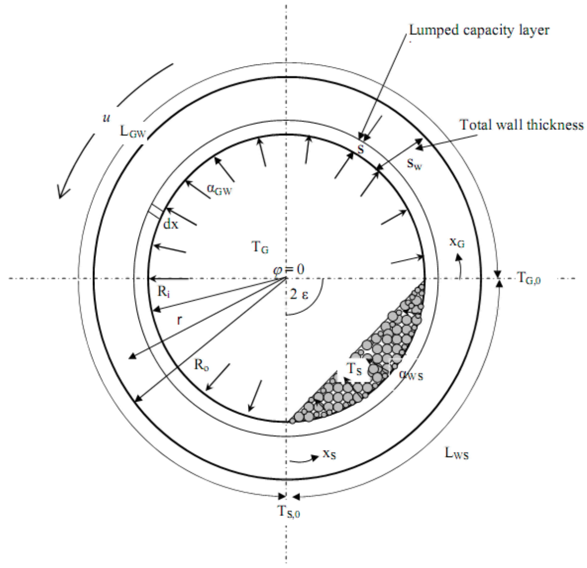

Figure3: Symbol used for the modelling of heat transfer

T_G is the gas temperature which is assumed to be constant through the cross section. ε_{eff} is the effective emissivity. The heat loss is approximated by the stationary heat conduction through the wall.

$$-\lambda \left. \frac{\partial T}{\partial r} \right|_{r=Ro} = q_L \qquad 0 \le \phi \le 2\pi \qquad (5)$$

Due to the closed ring, the following boundary conditions for the angular direction are valid

$$T(\varphi = 0°) \approx T(\varphi = 360°) \qquad (6)$$

$$\frac{\partial T}{\partial \varphi}(\varphi = 0°) = \frac{\partial T}{\partial \varphi}(\varphi = 360°) \qquad (7)$$

All these equations with mentioned boundary conditions were used for the Numerical analysis. Carslaw [18] has presented temperature distribution in a semi infinite body. In the radial direction and for the region where solid and wall are in contact, temperature profiles can be calculated using equation 8, where Z_{lc} is the active layer thickness, t_{WS} is the contact time between the rotating wall and the solid bed, 'a' is the thermal diffusivity of the wall. It can be seen that the thermal active layer depends on the material properties of the wall, heat transfer coefficient of wall-to-solid (α_{WS}), speed of rotation (n), filling angle (ε) and is independent of the kiln diameter.

$$\frac{T(r) - T_S}{T_{S,0} - T_S} = erf(Z) + e^{Bi \cdot (2 \cdot Z + Bi)} \cdot \left[1 - erf\left(Z + Bi \right) \right] \qquad (8)$$

Where,

$$Z_{lc} = \int_0^\infty \left[1 - \frac{T - T_S}{T_{S,0} - T_S}(Z) \right] dZ = \frac{s}{2\sqrt{a \cdot t_{WS}}} \qquad (9)$$

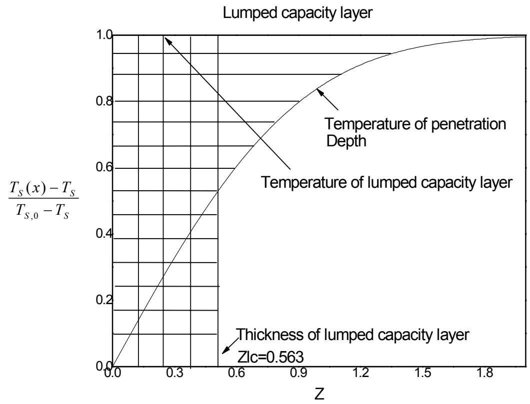

Figure 4: Active layer characteristics.

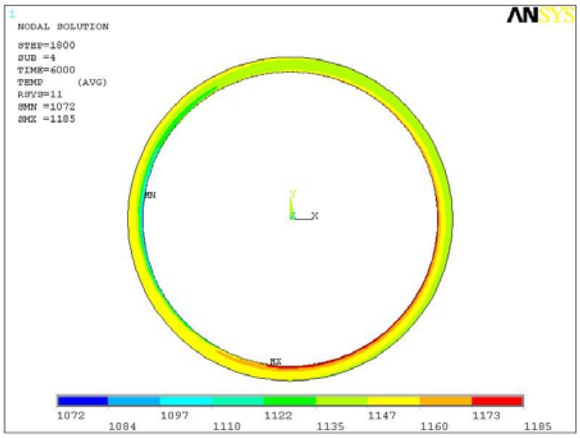

Figure 6a: Overall temperature distributions across the wall

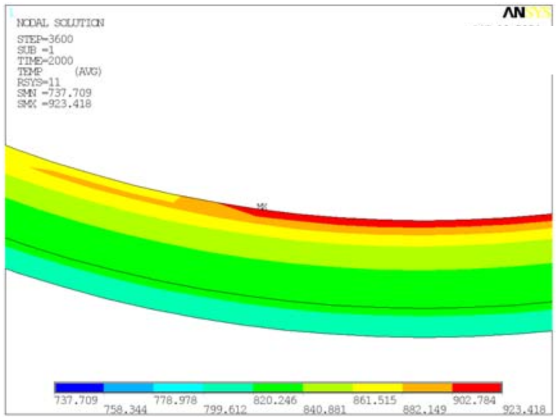

Figure 6b: Temperature distributions across the wall

Numerical simulation results

Meshing of the element is as shown in figure 5 represent close view for the finite element grid. Finer meshing gives better temperature distribution but only at the cost of higher computational efforts. Hence Optimised use of meshing plays an important role in the overall calculations of temperature distribution.

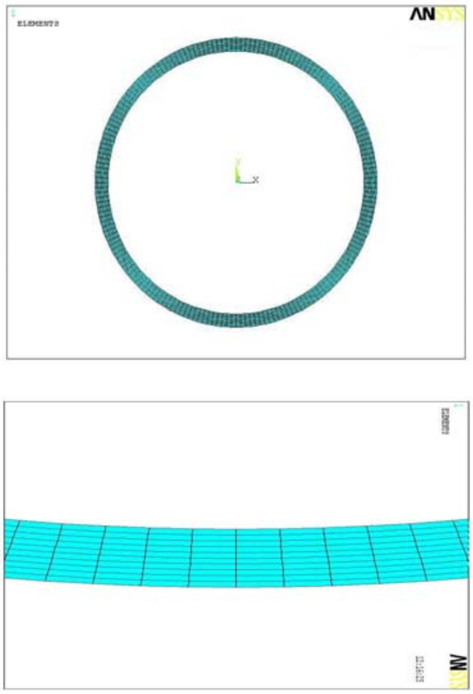

Figure 5: Numerical modelling grid for the Rotary Kiln

Temperature contour plot on the wall of the rotary kiln is as shown in the figure 6a and 6b. Different temperature distribution can be obtained on the wall of the Rotary kiln. At the boundary, the solid side wall gain heat from the solids and the temperature at this region decreases. At same time the gas side wall gain heat form gas, the

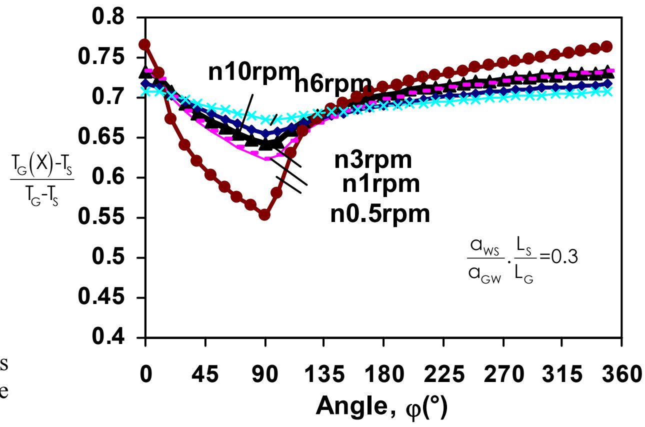

Figure 7: Temperature distributions across wall

temperature distribution has been observed. Figure 6 b shows that temperature at the inner side is more and it decreases towards the wall side. The fluctuation on the internal surface temperature of the kiln wall is presented in figure 7 as a dimensionless temperature form along the circumference. Kiln with 0.6 m ID with filling degree 10 is used for the simulation. A typical refractory material with a characteristic of ρ = 2100 kg/m³, cp = 1040 J/kgK, λ = 2 W/mK has been used. The thickness of 20 cm was selected for refractory wall. The rotational speed varies within a range of 0.5 to 10 rpm. Wall to solid and gas to wall heat transfer coefficients have same value of 200W/m^2 K. Temperature are set to be constant for the gas at 1273 K and the solid at 773 K. Kiln wall is alternately cooled and heated during each revolution by the hot gas and the cold solid respectively. The fluctuations of the kiln wall temperature decreases as the kiln speed increases. We can say for the infinite rotational speed, there is no fluctuation on the wall. $T_{S.0}$ is the initial point of the inner surface wall temperature in contact with the solid and $T_{G.0}$ is the point in contact with the gas. These two points gives maximum temperature fluctuation of the internal surface kiln wall. Figure 8a shows temperature profile inside the wall of the rotary kiln. Penetration depth is around 11 mm where all curve meet together. Only this thickness takes part in heat transfer process. This thickness is important in the heat transfer calculations. Temperature at the solid side decreases continuously and at the gas side it increases initially due to the regenerative heat phenomenon. To analyse the effect of various parameters on the temperature fluctuations, and equation has been developed.

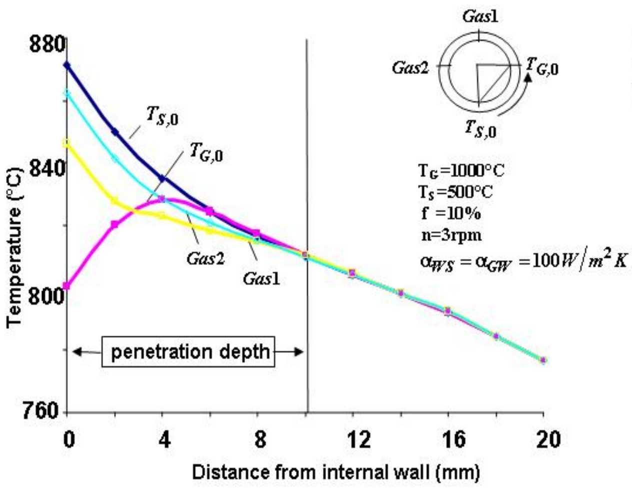

Figure 8a: Temperature fluctuations on the inner wall the kiln with ratio of heat transfer coefficient

Effect of filling degree on penetration depth has been studied thoroughly by using numerical simulation. Temperature of the gas is assumed 1000^{o}C and initial temperature of the solid is 500°C. Heat transfer coefficient of wall to solid and Heat transfer coefficient of gas to wall are 200 W/m2K and filling degree of 10% respectively , speed of rotation is maintained at 3 rotation per minute. Simulation results are shown in figure 7a. Penetration depth is about 11 mm. Similar simulation has been done for 14 mm for filling degree of 20%, as shown in figure 8 b, which indicate that with increase in the filling degree, the penetration depth is also increases. Figure 9 represents the comparison of temperature profiles using an analytical and the numerical solution at three different value of gas to wall heat transfer coefficients with

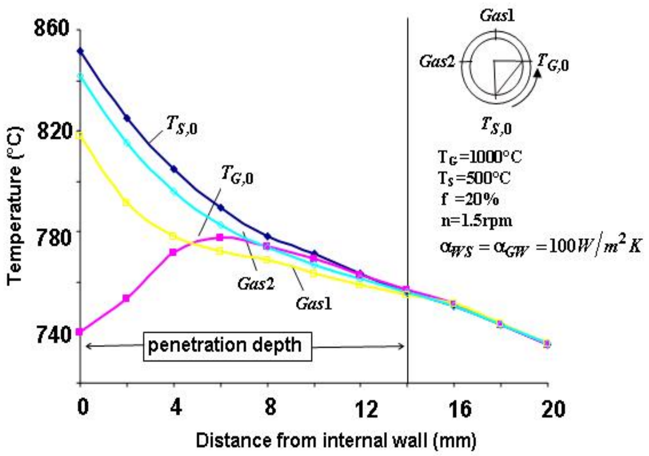

Figure 8b: Temperature fluctuations on the inner wall the kiln with ratio of heat transfer coefficient

typical rotational speed of 3 rpm. A satisfactory match between numerical and analytical results has been observed.

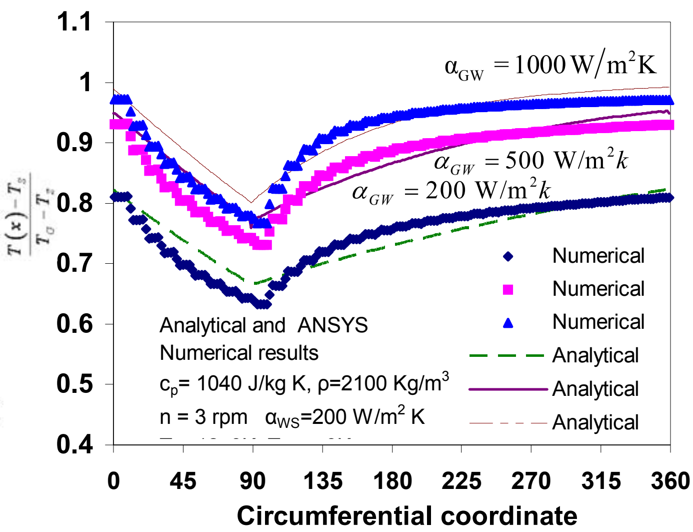

Figure 9: Comparison of the Analytical and Numerical temperature profile on the inner wall

Higher heat transfer gives high dimensionless temperature.

In figure 10 the temperature fluctuations is plotted against the ratio of the wall to solid heat transfer coefficient and the heat transportation coefficient at typical rotational speed of 3 rpm. At high value of the heat transportation coefficient, the heat is transferred perfectly from wall to solid. The fluctuations at the inner wall decreases at higher value of the wall to solid heat transfer coefficient. This phenomenon is explained in [12]. Numerical calculations have been done with two different diameters. It has been noticed diameter does not have any influence on the temperature fluctuation. It closely matches with the analytical results.

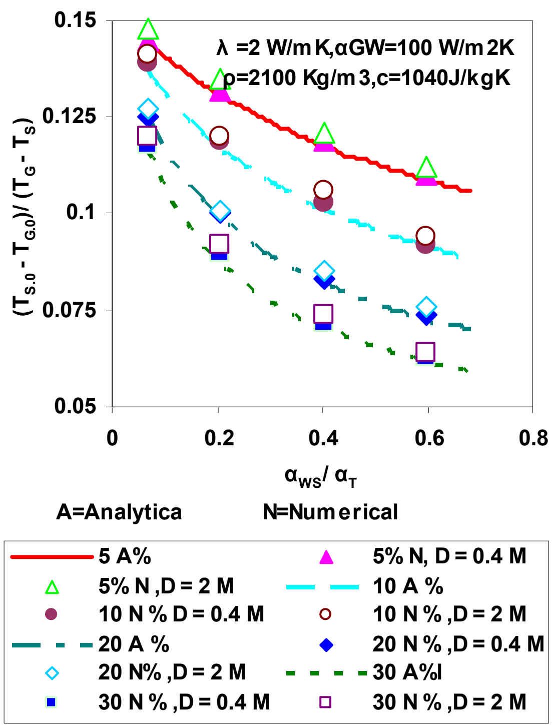

Figure 10: Comparison of the Analytical and Numerical temperature profile on the inner wall

CONCLUSION

The heat transfer model for the temperature fluctuation in the wall of rotary kiln has been implementation in finite element package Ansys. The results clearly indicate that temperature fluctuation decreases with increases in rotation speed. A result clearly shows that temperature fluctuations are independent on the diameter of the rotary kiln. At infinite rotation speed, no temperature fluctuation can be observed. Numerical and analytical results are well match with each other. Penetration depth which has an important role in the heat transfer phenomena has been studied thoroughly. It is observed that for higher filling degree, the penetration depth is also large.

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