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# An Investigation of Heat Transfer in Vertical Shaft Kiln Process of Cement Manufacture: Part II – Conduction and Radiation

Dipankar Neog[1], PG Rao[2], ML Das[3], Pranab Barkakati[4]
[1, 4] *CSIR-North East Institute of Science and Technology, Jorhat, Assam, India*
[2] *University of Science and Technology, Meghalaya, India*
[3] *Mahatma Gandhi Institute of technical Education and Research, Navsari, Gujarat, India*

***Abstract— The heat transfer inside the vertical shaft kiln (VSK) for cement manufacture is a complex phenomena involving all the three modes of convection, conduction and radiation heat transfer inside the packed bed moving column. The convective mode of heat transfer was investigated and reported in part-I of this present study [1]. In this part of investigation, we studied the effect of conduction and radiation heat transfer on the clinkerization process using varying feed size and air flow rates in an experimental prototype kiln. The effective thermal conductivity $k_e$ was determined under various air flow rates and correlations were compared with existing heat transfer models suggested by different researchers. It was observed that the Maxwell-Eucken model best represented the conduction heat transfer in the VSK process.***

***Keywords - Vertical Shaft Kiln (VSK), Packed bed heat transfer, Effective thermal conductivity, Convection, Conduction, Radiation.***

## I. INTRODUCTION

Conduction and radiation mode of heat transfer are two important transport phenomena in the vertical shaft kiln (VSK) process of cement manufacture in addition to the convection mode of heat transfer that takes place in the packed bed of the VSK. Conduction and radiation have close interactions with one another and hence the parameters determined have effective values rather than absolute values. The black meal process of cement manufacture and the vertical shaft kiln are illustrated in details in our previous work [1]. The conduction heat transfer propagates in both radial and axial directions. As the packed bed is considered as continuum and conduction is affected by other modes of heat transfer like convection and radiation, effective heat transfer is considered in the system and effective radial thermal conductivity ($k_{er}$) and effective axial thermal conductivity ($k_{eax}$) were determined at different air flow rates. It has been reported by many researchers that, conduction is significantly affected by convection and radiation mode of heat transfers [2, 3]. The effect of radiation is usually combined with the other two modes of heat transfer and two heat transfer parameters are introduced to represent the overall system as effective thermal conductivity due to radiation ($k_{rad}$) and overall radiation heat transfer coefficient ($h_{rad}$). In the present work the thermal parameters for the combined effect of radiation and conduction in the VSK process of cement making were determined using an experimental prototype kiln [1], and the thermal conductivity $k_s$ for the solid feed materials were determined experimentally using an electrical heating technique.

## II. REVIEW OF LITERATURE ON PACKED BED HEAT TRANSFER-CONDUCTION AND RADIATION MODE

Many researchers have put forward different conductive heat transfer correlations which can be generalised in to a simple formula as [4, 5]

$$k_{er} = A + B \times \mathrm{Re}_p \text{ ----------------- } (1)$$

Widely used correlations of conduction heat transfer within a range of Reynolds Numbers (*Re*) resembling the present investigation are listed in table – I. It has been reported in our earlier studies [1] that there is no significant radial temperature gradient at any particular axial distance of the bed. Hence the effective axial thermal conductivity $k_{eax}$ is considered as the overall heat transfer coefficient of the system.

The basic equation of thermal conductivity is expressed as

$$q_{cond} = \frac{k_e A_{C,S}}{L}(T_1 - T_2) \text{ ----------------- } (2)$$

Where $k_e$ is the effective coefficient for the combined effect of solid and fluid materials. The individual conductivities of solid and fluid are not related to each other either in series and parallel combination [6]. The system could be described by an equivalent parallel composite wall consisting of a fluid and solid regions of length related to the packed bed porosity *ε*. The

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values of the maximum and minimum effective coefficients can be expressed as

$$k_{e,\min} = \frac{1}{(1-\varepsilon)/k_s + \varepsilon / k_f} \qquad \text{-------} \ (3a) \qquad\qquad k_{e,\max} = \varepsilon\, k_f + (1-\varepsilon) k_s \qquad \text{-------} \ (3b)$$

Where, $\varepsilon$ is the bed voidage, $k_e$ & $k_f$ are the heat transfer coefficient of solid and fluid respectively.

TABLE I

CONDUCTIVE HEAT TRANSFER CORRELATIONS USED IN THE PRESENT STUDY

| Conductive Heat Transfer Equations | Applications and Considerations | Reference |
|---|---|---|
| $\frac{k_{eax}}{k_f} = (0.9069)(2)\left(\frac{k_s}{k_s-k_f}\right)^2\left(\ln\frac{k_s}{k_f} - \frac{k_s-k_f}{k_s}\right) + 0.0931$ | Considering $k_{eax}$ as a function of $k_s$ and $k_f$ | Kunii and Smith [7] |
| $k_e = k_e^0 + 0.11 \times (C_{pg} d_p u)$, Where $k_e^0 = 0.9065\left[\frac{2}{(1/k_f)-(1/k_s)}\right]\left[\frac{k_s}{k_s-k_f} \times \ln\left(\frac{k_s}{k_f}\right) - 1\right]$ | Conductivity of bed with stagnant fluid was also considered. | Yagi and Kunii [8] |
| $k_{eax} = k_f + \frac{k_s}{1 + \frac{(16/3)k_s(h_{fp}d_p)^{-1} + (0.1/k_s)^2}{(1-\varepsilon)(D_t/d_p)^2}}$ | Packed bed and particle geometry in the form of $(D_t/d_p)$ was considered. | Dixon and Cresswell [9] |
| $k_{con} = \frac{2k_f}{1-(k_f/k_s)}\left(\frac{\ln(k_s/k_f)}{1-(k_f/k_s)} - 1\right)$ | Considering the packed bed as a combustor-heater system resembling the present application. | Mohamad et. Al. [10] |
| $\log\frac{k_e}{k_f} = \left(0.280 - 0.757\log\varepsilon - 0.057 \times \log\frac{k_s}{k_f}\right) \times \log\frac{k_s}{k_f}$ | Equation derived for spherical particles considering bed voidage | Krupiczka [11] |
| $k_e = \frac{k_s + 2k_f + 2(k_s-k_f)(1-\varepsilon)}{k_s + 2k_f + (k_s-k_f)(1-\varepsilon)} k_f$ | It was a fundamental correlation derived for powdered material and widely used by different researchers | Maxwell [12] |
| $k = k_s \frac{1-\left(1-A\frac{k_f}{k_s}\right)\varepsilon}{1+(A-1)\varepsilon}$ where, $A = \frac{3k_s}{2k_s + k_f}$ | It is an improvement over the Maxwell model. | Maxwell- Eucken [13] |

It is reported that the radiative heat transfer co-efficient $h_{rad}$ and radiative contribution of thermal conductivity $k_{rad}$ are functions of third power of temperature [14]. For analysing the radiation effect, the correlations put forward by Wakao & Kato and Doraiswamy & Sharma are widely used [15, 16]

$$h_{rad} = \frac{0.2268}{(2/\varepsilon) - 0.264}\left(\frac{T}{100}\right)^3 \qquad \text{-------} \ (4)$$

$$k_{rad} = 4 \pm g d_p T^3 \qquad \text{-------} \ (5)$$

## III.METHODS AND MATERIALS

Experiments on conductive and radiative heat transfer studies were carried out in a prototype kiln and data acquisition to computer was made through data logger. The details of the experimental set-up was discussed and presented in our previous work [1]. The total amount of heat developed in the clinkerization process was determined by using thermo gavimetric (TGA) and differential scanning calorimetry (DSC) (Jupiter STA 449 F3 from NETZSCH, GmBH, Germany) technique. The design of the raw mix, the physico-chemical properties of the raw materials, preparation and burning of the green nodules were all discussed in ourprevious part of this publication [1]. The measurement of thermal conductivity of solid, $k_s$ is carried out using an experimental set-up where a resistive heating coil of known wattage is used to convert electrical energy to thermal energy. The thermal flux created is aligned unidirectional using a heat flux smoother. Proper insulation wall is provided to make an adiabatic condition inside the chamber (figure 1). Two thermocouples (K type with Ni-Cr / Ni-Al) are placed in the heat flux path at two measured heights. Experiments are carried out by placing the test packed bed material samples above the heat flux smoother and providing at different temperatures by varying the input voltage through a variac and continued till achievement of steady state. $k_s$ for the sample is determined by solving the Fourier's law and using the following equation

$$\int_{X_1}^{X_2} q_x\, dx = \int_{T_1}^{T_2} -k_s A_{C,S}\, dT \qquad \text{or} \qquad k_s = \frac{q_x \, . \, X}{A_{C,S}(T_2 - T_1)}$$

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$$\Rightarrow k_s = \frac{V.I.X}{A_{C,S}(T_1 - T_2)} \quad \text{where } X = (X_2 - X_1) \text{ and } q_x = V \times I \qquad \text{-------} \; (6)$$

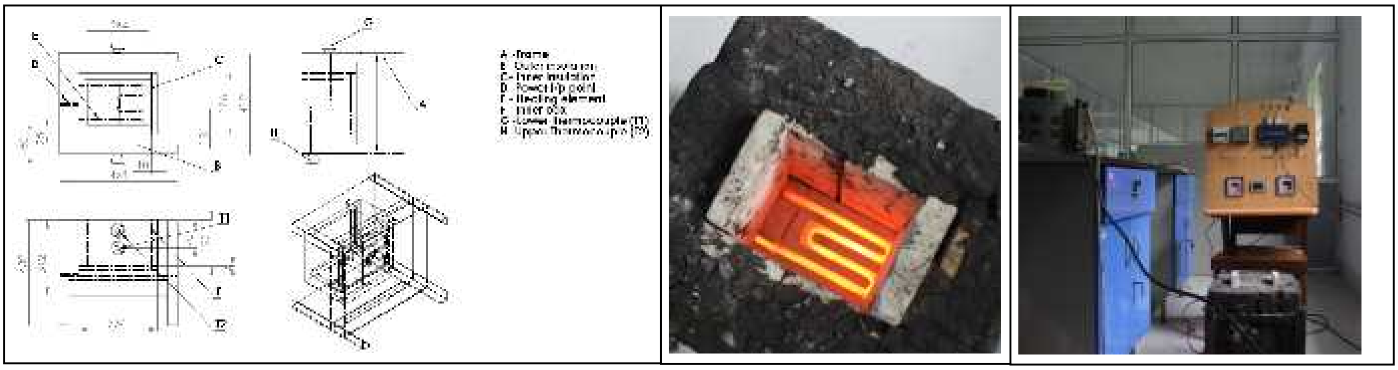

Figure 1: Schematic design of the experimental set-up for measurement of $k_s$

## IV. RESULTS AND DISCUSSIONS

### A. *Conduction Heat Transfer Model*

The effective thermal conductivity $k_e$ was experimentally determined in the prototype packed bed kiln at different temperature values recorded against the clinkerisation time inside the kiln. The time vs. $T_{bed}$ plot was presented in our earlier communication [1]. The heat flow due to conduction, $q_{cond}$ was evaluated with the help of TGA/DSC and the plots are shown in figure 2. While taking the TGA/DSC plots two temperature points in the clinkerisation zone viz. 1300$^0$C and 1450$^0$C are considered. It was observed that for different air flow rates the solid phase temperatures recorded by two consecutive thermocouples were different. The corresponding energy released per unit mass was obtained from the TGA/DSC plot and the total thermal energy ($q_{total}$) was calculated using the equation $q_{cond} = q_{total} - q_{conv}$, where, $q_{conv}$ was determined in our previous work [1].

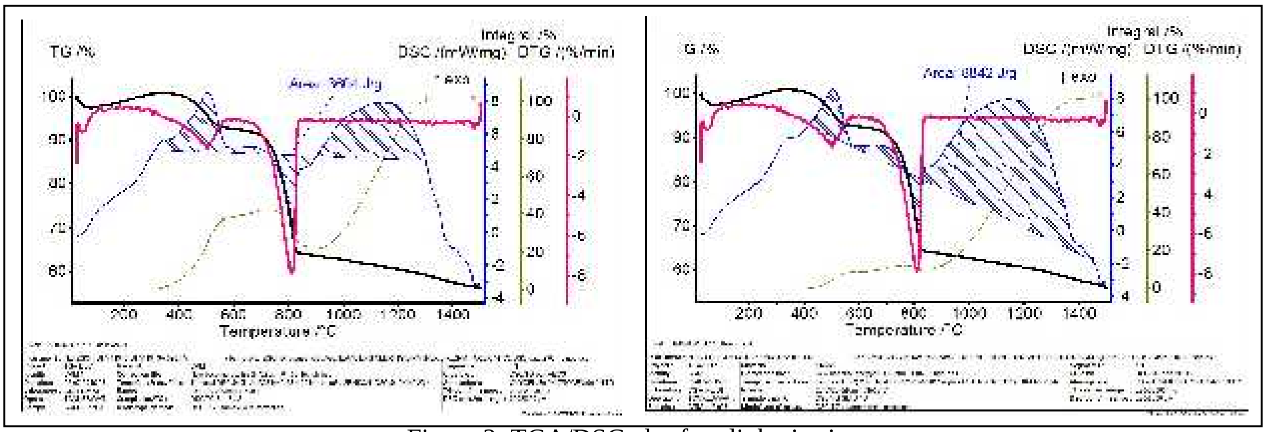

Figure 2: TGA/DSC plot for clinkerisation

The experimental and model predicted $k_e$ values determined at 1300 $^0$C and 1450$^0$C with three different feed material sizes are compared and presented in figure 3. It was observed that none of the selected models could represent the process and the experimental results could signify only for nodule size of 7.02 mm at an average packed bed temperature of 1300$^0$C. The *Kunii and Smith* model was close to the experimental values for air flow rate of 2000 litre per minute (lpm) and for the other two flow rates of 2500 lpm and 3000 lpm, *Yagi and Kunii* model was more significant. At high air flow rates of 3000 lpm *Maxwell-Eucken* model showed close approximation. The nonrepresentation of the model correlations may be due to reasons that all the models available and selected were derived for non reacting systems at unsteady state conditions.

### B. *Determination Of Solid Phase Conductivity $K_s$*

$K_s$ was determined at six different temperature ranging from 72$^0$C to 221$^0$C. The temperature vs. time plot taken as two different thermocouple positions in the heat chamber is presented in figure 4.

The values of $k_s$ at the clinkerization temperature zone beyond 221$^0$C was extrapolated using the best fitting correlated equation as shown in the figure 5. The correlation equation is an exponentially decay equation with $R^2$=0.9986 and is represented as follows. The results are shown in table II.

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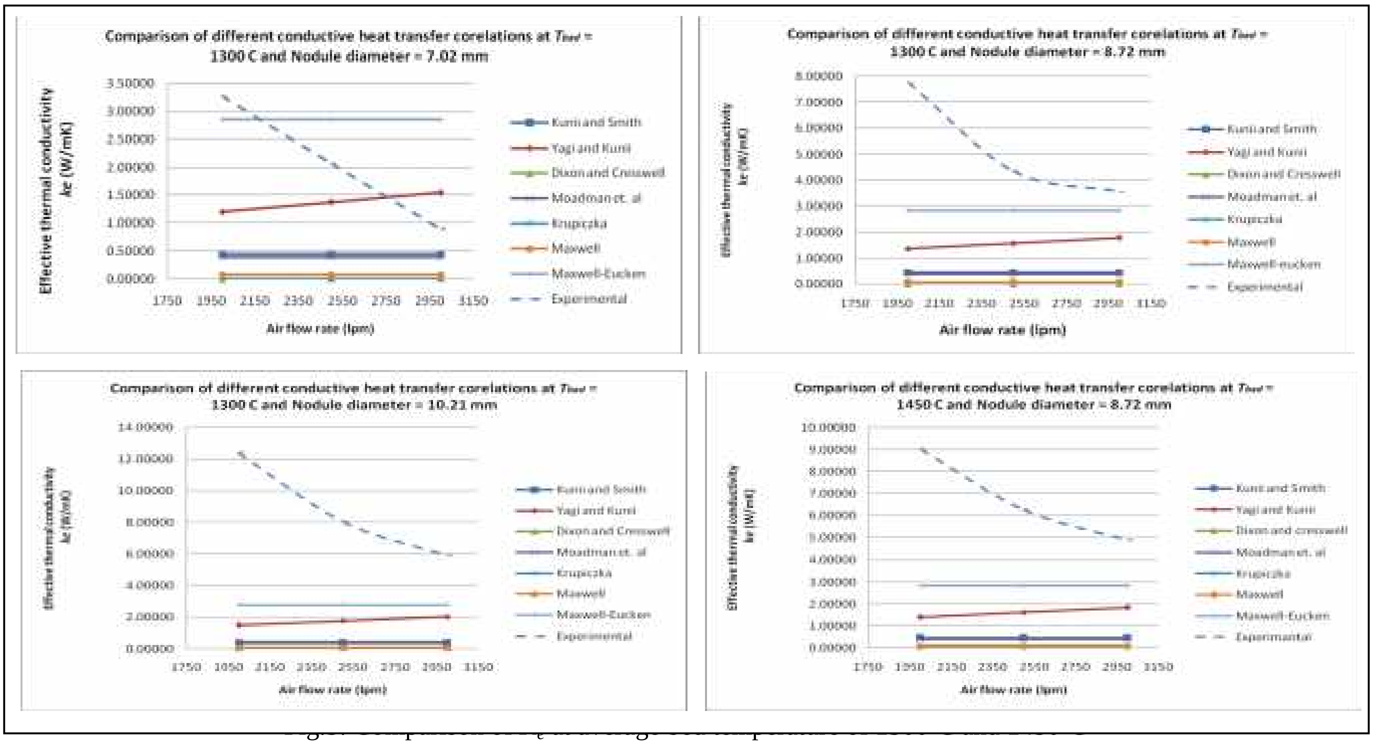


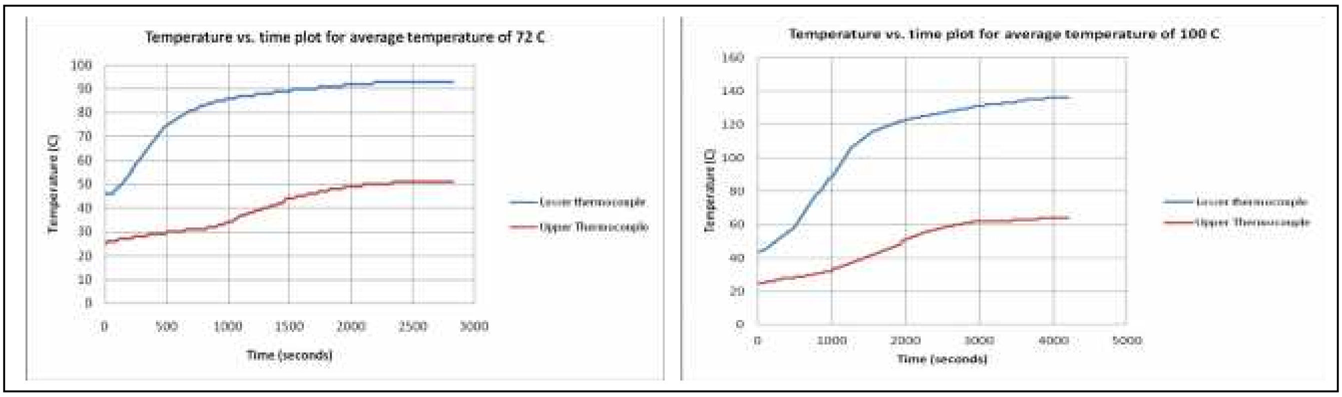


Figure 4: Temperature vs. time plot for determination of solid conductivity.

$$k_s = 1506.4 \times e^{-\left(\frac{T}{65.649}\right)} + 4.673 \quad \text{------------ (7)}$$

Using equation (7) $k_s$ at 500$^0$C, 1300$^0$C and 1450$^0$C are estimated as 4.6846, 4.6730 and 4.6730 W/m.K respectively

*C. Effect Of Air Flow Rate On Effective Thermal Conductivity $K_e$*

Figure 6 shows the plot of effective thermal conductivity $k_e$ vs. air flow rate. It was observed that $k_e$ decreases, with increase of air flow rate. This is because of reason that $k_e$ has combined effect of both solid and fluid conductivity. With the increase of air flow rate the convective heat transfer becomes prominent compared to the conductive heat transfer effect. Similar observations were also reported by earlier investigators. [4, 17]. Different trend was observed in the experiment with packed bed temperature at 1450$^0$C and at lower bed voidage (particle diameter 7.02 mm), where increasing air flow rate increased the effective thermal conductivity. At 1450$^0$C, the solid-solid reaction takes place in the bed and the bed behaves as partially semi-solid in the melt phase. At this stage the system behaves like a single phase loosing its packed bed identity. However, at air flow rate of 3000 lpm, it was observed that $k_e$ decreases. The reason may be attributed to sufficient channelling for air passage in the melt phase which over-rides the limp effect in the bed and the system reverts back to near packed bed mode. Again at the same temperature this behaviour is not observed for nodule size of $d_p$ = 8.72mm. This may be due to the reason that at this larger nodule size and higher bed voidage the convective effect of heat transfer do not interfere the effective thermal conduction in the bed.

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TABLE II

SOLID THERMAL CONDUCTIVITY VALUE AT DIFFERENT TEMPERATURE

| Sl. No | Steady state lower thermocouple reading $T_1$ ($^0$C) | Steady state upper thermocouple reading $T_2$ ($^0$C) | Average Temperature ($^0$C) | Voltage (Volt) | Current (Amps) | Power (Watt) | Cross Sectional Area (m$^2$) | Bed Thickness (m) | Solid thermal conductivity, $k_s$ (W/m.K) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 93 | 51 | 72 | 140 | 2.50 | 350.0 | 0.0465 | 0.07 | 12.56 |
| 2 | 136 | 64 | 100 | 150 | 3.10 | 465.0 | 0.0465 | 0.07 | 9.73 |
| 3 | 180 | 80 | 130 | 160 | 3.31 | 529.6 | 0.0465 | 0.07 | 7.98 |
| 4 | 234 | 92 | 163 | 175 | 3.62 | 633.5 | 0.0465 | 0.07 | 6.72 |
| 5 | 289 | 89 | 189 | 195 | 4.00 | 780.0 | 0.0465 | 0.07 | 5.88 |
| 6 | 356 | 86 | 221 | 220 | 4.50 | 990.0 | 0.0465 | 0.07 | 5.52 |

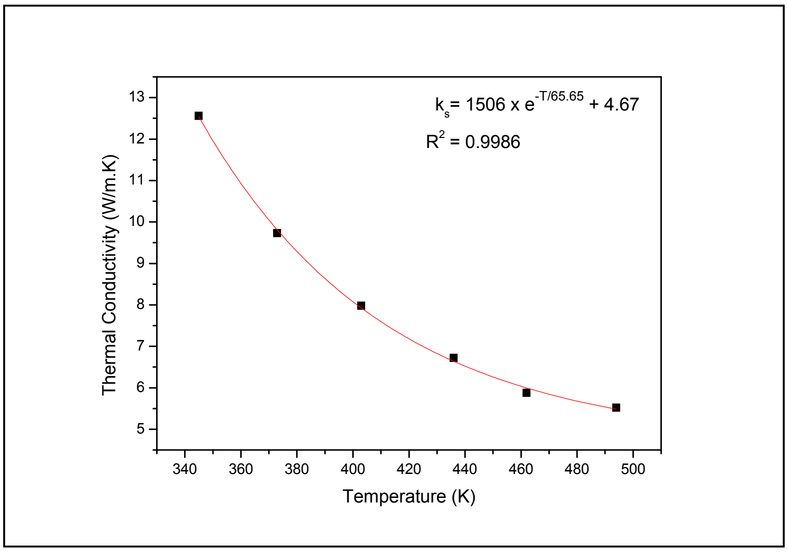


Figure 5: Temperature vs. thermal conductivity correlation

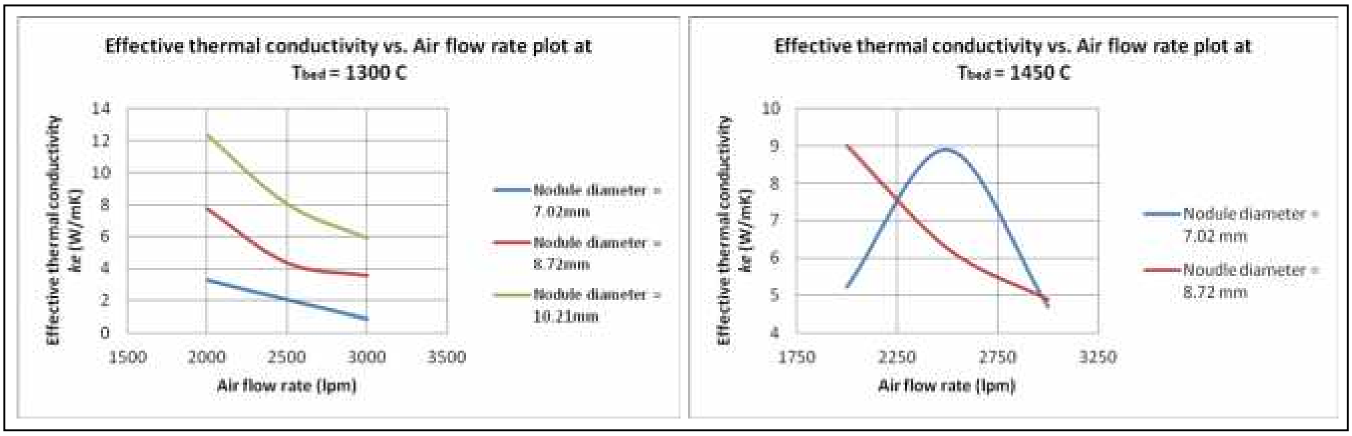


Figure 6: Effective thermal conductivity vs. air flow rate

### *D. Effect of Nodule Diameter On Effective Thermal Conductivity $K_e$*

Figure 7 shows the plot of effective thermal conductivity $k_e$ vs. nodule diameter $d_p$. It was observed that the value of effective thermal conductivity $k_e$ increased with the increase of nodule diameter $d_p$. The same increasing trend was also observed for all other air flow rates at 1300$^0$C. This is due to the fact that with the increase of nodule sizes, total surface area increases and the convective effect on effective thermal conductivity also increases and the effect in the change in the air flow rate was insignificant. Also at higher air flow rate (2500 lpm) & 1450$^0$C, the $k_e$ value decreases due to the formation of melt phase during the solid-solid clinkering process in the packed bed kiln.

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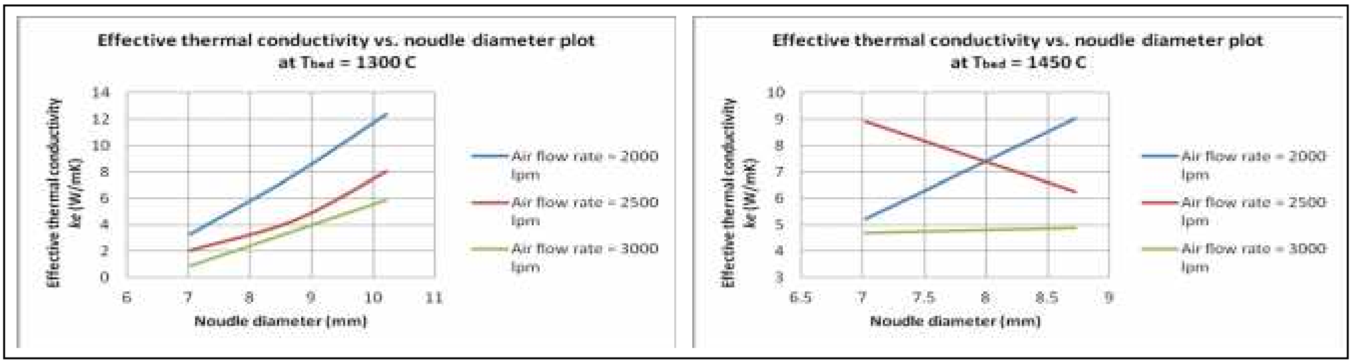


Figure 7: Effective thermal conductivity vs. nodule diameter

*E. Radiation Heat Transfer Effect*

The effect of radiation heat transfer in the process was evaluated from correlation represented by equation 4 & 5. Parameters used in the correlation have been determined experimentally as per procedures already indicated. Table III represents the evaluate values of the radiative heat transfer co-efficient $h_{rad}$ and radiative contribution of thermal conductivity $k_{rad}$ at different bed temperatures of the kiln. Result shows that the radiative heat transfer co-efficient and radiative contribution of thermal conductivity increases with increase in the temperature across the kiln bed.

TABLE III

RADIATIVE THERMAL CONDUCTIVITY AND RADIATIVE HEAT TRANSFER COEFFICIENTS AT DIFFERENT BED TEMPERATURE

| Sl No. | Packed bed Temperature ($^0$K) | Particle Diameter (m) | Bed Voidage, ε | Radiative heat transfer co-efficient, $h_{rad}$ | Radiative thermal conductivity*, $k_{rad}$ |
|---|---|---|---|---|---|
| 1 | 773 | 0.00702 | 0.3990 | 22.0599 | 7.2147 |
| 2 | 773 | 0.00872 | 0.4033 | 22.3119 | 8.9618 |
| 3 | 773 | 0.01021 | 0.4144 | 22.9630 | 10.4931 |
| 4 | 1573 | 0.00702 | 0.3990 | 185.8876 | 60.7944 |
| 5 | 1573 | 0.00872 | 0.4033 | 188.0115 | 75.5167 |
| 6 | 1573 | 0.01021 | 0.4144 | 193.4979 | 88.4204 |
| 7 | 1723 | 0.00702 | 0.3990 | 244.2981 | 79.8976 |
| 8 | 1723 | 0.00872 | 0.4033 | 247.0894 | 99.2460 |
| 9 | 1723 | 0.01021 | 0.4144 | 254.2998 | 116.2043 |

* Gravitational acceleration $g$ = 9.81 m/s$^2$ and Stefan Boltzmann Constant $\sigma$ = 5.6704E-08 WmK$^{-4}$

## V. CONCLUSIONS

It can be concluded from the investigation that the correlation of *Maxwell-Eucken* has the closest approximation in the conductive heat transfer in packed bed vertical shaft kiln process of cement manufacture. However, at 1300$^0$C *Kunii and Smith* and *Yagi and Kunii* models better represents the conductive heat transfer in the kiln. The solid phase conductivity $k_s$ can be best represented by the derived correlation (7). It is also concluded that at the clinkerization temperature (1450$^0$C), the heat transfer in the packed bed changes its behaviour because of the solid state melt phase reaction in the clinkerization process.

## VI. NOMENCLATURE

$A_{c,s}$ : Cross sectional area of solid bed (m$^2$)
*A, B, C* : Constants.
$c_{pg}$ : Specific heat of gas at constant pressure (J kg$^{-1}$ K$^{-1}$)
$d_p$ : Diameter of the spherical nodules (m, mm)
$D_t$ : Diameter of the kiln (m, mm)
g : Acceleration due to gravity (= 9.81 m.s$^{-2}$)
$h$ : Convective heat transfer coefficient (Wm$^{-2}$K$^{-1}$)
$I$ : Current (amps)
$k$ : Thermal conductivity (Wm$^{-1}$K$^{-1}$)
$L$ : Length of the bed (m)

| | |
|---|---|
| $q$ | : Rate of heat flow (W) |
| $Re_p$ | : Reynolds Number = ($°ud_p / \mu$) |
| $T$ | : Temperature (K) |
| $u$ | : Velocity of air (m $s^{-1}$) |
| $V$ | : Voltage (volt) |
| $X$ | : Distance (m) |
| $x, y, z$ | : Coordinates |
| $\sigma$ | : Stefan Boltzmann Constant (= 5.670373 x $10^{-8}$ W.$m^{-2}$.$K^{-4}$) |
| $\varepsilon$ | : Bed voidage. |

*Subscripts and Superscript*

| | |
|---|---|
| *ax* | : Axial |
| *cond* | : Conduction |
| *conv* | : Convection |
| *e* | : Effective |
| *f* | : Fluid |
| *p* | : Particle |
| *r* | : Radial |
| *rad* | : Radiation |
| *s* | : Solid |
| *0* | : Stagnant |

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