Report on

MODELING OF CLINKER COOLERS: Applications to Reduction in Energy Consumption

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Abstract

Grate coolers are extensively used in cement industry to recover heat from hot clinkers coming out of rotary kilns. Heat transfer in coolers indirectly controls the performance of the rotary kiln and is therefore crucial in a cement industry. In this report, we present a computational model to capture heat transfer in grate coolers. The schematic of grate cooler considered in the present study is shown in Figure 2. The solids of uniform particle size and constant porosity were assumed to move in a plug flow with constant grate speed. Air was assumed to enter in a cross flow mode with respect to solids as shown in Figure 1a. To get the temperature profiles of solid bed and air, the length and the height of clinker bed in the cooler were subdivided into individual balance segments. The energy balance was solved for individual segments. Conductive heat transfer was considered for solids in both x and y directions. Convective heat transfer coefficient between air and solids was calculated from empirical correlation assuming solids as packed bed. The boundary conditions used are shown in Figure 1a. The model equations obtained from energy balances were solved using TDMA Technique. Several numerical simulations were carried to understand the influence of operational parameters like grate speed, solids inlet temperature and particle size, and airflow rate on the performance of the cooler. The presented computational model and the simulation results will be helpful in developing better understanding of heat transfer in grate coolers and to improve the cooler efficiency by choosing optimized operating parameters.

Key words: Grate cooler; Rotary Kiln; Clinker; TDMA technique; Under-relaxation

1. INTRODUCTION

Grate coolers are widely used in cement industries to recover heat from hot clinkers coming from the rotary kiln. The schematic of a cement industry is shown in Figure 1.

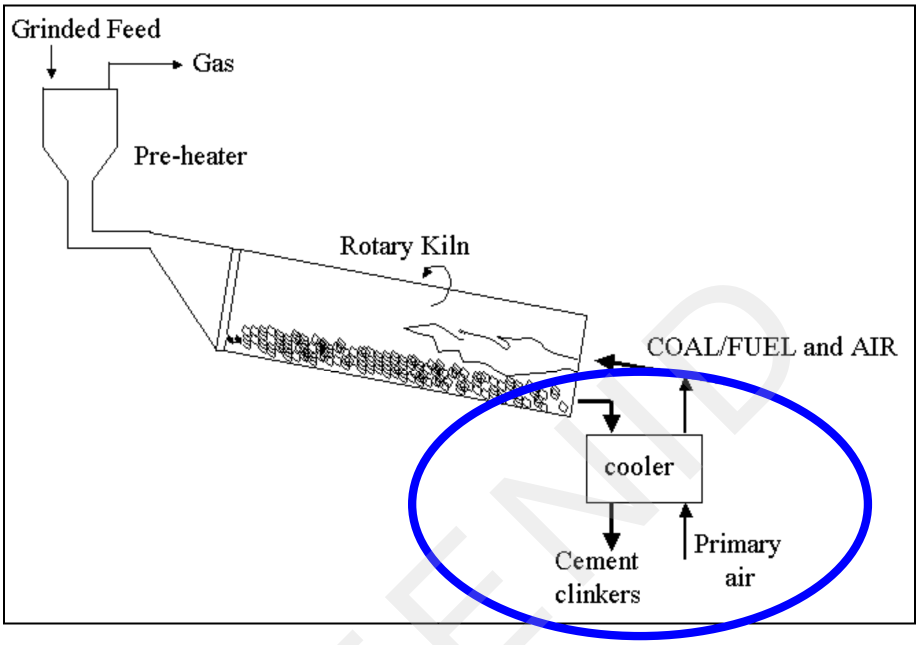


Figure 1: Schematic of Cement manufacture

The raw meal is first fed to pre-heaters where the raw meal get heated, recovering heat from the hot gases coming from the kiln and calciner. Then it goes to calciner where 60–80 % calcination takes place. And then partly calcined charge is fed slowly to a rotary kiln where calcinations reactions are completed. The outlet temperature of hot clinkers and a part of melt coming out from the rotary kiln is approximately 1673 K. These hot clinkers should be cooled to a temperature around 400 K, by recovering heat from them, which can be used for any other process. In the same time the combustion air required for the burning process should be preheated to a temperature level such that the fuel consumption for clinker formation in the rotary kiln is minimum. So to fulfill both the purposes grate coolers are used in cement industries. Cooling in a grate cooler is achieved by passing a current of air upwards through a layer of clinker bed lying on the air-permeable grate. So the cooler acts as a pre-heater unit for the air used for coal combustion in rotary kiln and calciner.

A typical cement plant producing about 3000 TPD clinkers requires energy input of about 650-750 kcal/kg clinker (in terms of coal fed to the plant). Considering the volumes involved in manufacturing cement, it is worthwhile to explore new ways to reduce energy consumption per unit weight of product. To make this process efficient the efficiency of the cooler plays a key role. Because this recovers heat from the hot clinkers and pre-heat the air used for combustion in calciner and rotary kiln. Heat from the clinkers coming out from the cooler will not be recovered again and that will be actual loss to the system. Therefore, to decrease the energy consumption in a cement plant it is worthwhile to find the optimum values of operating parameters for the cooler.

The energy consumption in the cooler is governed by the energy required to drive the clinker bed and the heat losses to the surroundings from the cooler. The clinker bed can be transported using two types of grates: Traveling grate or Reciprocating grate. In traveling grate coolers a traveling grate transports clinker. On the other hand in reciprocating grate coolers clinker is transported by stepwise pushing of the clinker bed by the front edge of alternate row plates. For a given mechanism in the cooler the energy required for the motion of clinker bed is more or less constant. Therefore, the efficiency of cooler mainly depends on how effectively the heat is recovered from the clinkers and the losses from the cooler surface (conduction, convection, radiation) to surroundings. Clinker temperature variation in the cooler has an important influence on the quality of the cement produced from the plant. An efficient cooler will be in which outlet temperature of the clinker is minimum with suitable properties. So to improve the efficiency of the cooler used in cement industries we should choose optimum cooling air rate, clinker input rate, Clinker inlet temperature, cooler length, number of openings for air, and grate speed.

Therefore, a program was undertaken to develop detailed computational models for simulating the operational parameters for grate coolers. The model presented in this report is based on expression for calculating the heat transfer between cement clinker and air particles.
In the next section we present a model for grate cooler along with the computational methodology. Finally we discuss few results with our conclusions.

2. Simulation model for a grate cooler

2.1 Subdivision of the cooler into balance segments

Using finite volume method the length and the height of the clinker bed in the grate cooler are subdivided into individual balance segments for calculation of heat transfer. The results presented here were calculated for a cooler in which the length was subdivided in to 120 balance segments and the height into 90 segments as shown in Figure. 2. The dimensions of a cell were so small such that we can take that each the cell to be uniformed mixed, means that each cell is at a constant temperature equal to the outlet temperature from that cell.

2.2 Model equation for grate cooler

Model equations for general mass and energy balance in a traveling grate cooler are discussed below. As shown in figure 1a the solid bed is moving in horizontal direction and the air is moving in cross flow to bed (in perpendicular direction to the grate). The grate speed is given by v_g. The geometry of the bed has been taken as rectangular. The length of the solid bed is L, height H, and the width is W. We have divided the clinker cooler into n segments along the length and m along the height. Now we can write energy and mass balance for air and solid in each subdivision separately.

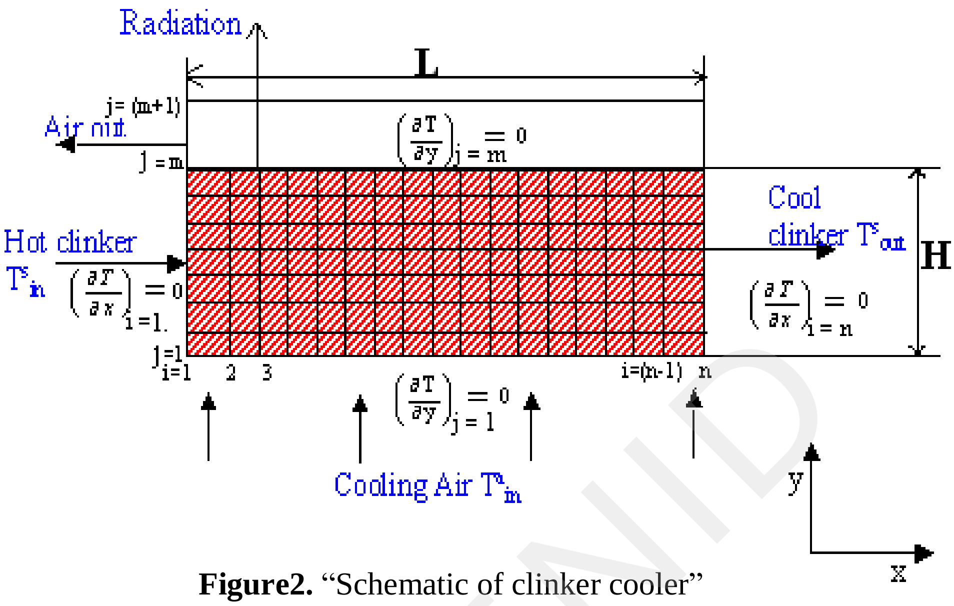


Figure2. "Schematic of clinker cooler"

2.2.1 Mass balance for solids

The solids were assumed in a plug flow along x direction. So the mass flow rate of solids will remain unchanged through out the system and the mass flow rate through each balance segment will be same as the inlet mass flow rate of the solids. Therefore, the mass flow rate of solids in each subdivision will be

$$m^s_{(i,j)} = m^s_{in}\left[\frac{\Delta y}{H}\right] \quad (1)$$

2.2.2 Energy balance for solids

A energy balance equation for solids was derived for a general (i ,j) subdivision. As shown in **Fig. 3** the solids are coming at a high temperature taken as T_e^s to this cell. They are losing heat by convection and conduction to the cooling air coming from below in this subdivision and exiting from the cell at a temperature T_P^s. The cooler is in continuous mode and we are assuming it to be stead. So there will be no accumulation of energy in any subdivision. Now apply the energy balance on the solids in this subdivision.

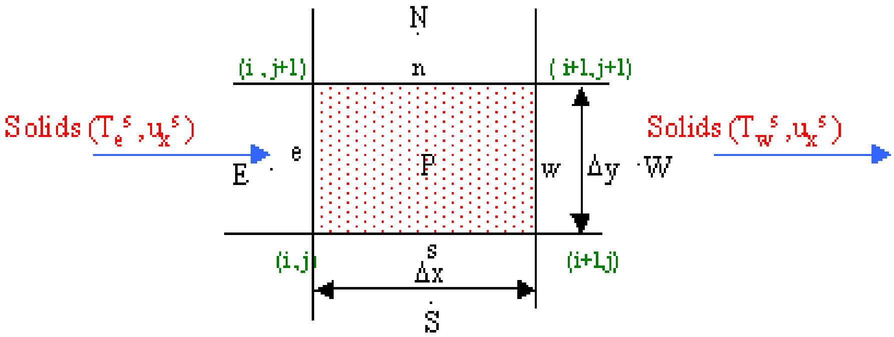


Figure 3. General (i,j)th cell for solid balance

In this subdivision there will be heat exchange between cement clinkers and air by convection. There will be conduction from cement clinker subdivision to the all-neighboring cement clinkers subdivision represented by E, W, N, and S. So by applying the energy balance on this subdivision:

$$\frac{\partial(\rho^s(1-\varepsilon)u_x^s c_p^s T^s)}{\partial x}+\frac{\partial(\rho^s(1-\varepsilon)u_y^s c_p^s T^s)}{\partial y}=$$
$$\frac{\partial\left\{(1-\varepsilon)K^s\frac{\partial T^s}{\partial x}\right\}}{\partial x}+\frac{\partial\left\{(1-\varepsilon)K^s\frac{\partial T^s}{\partial y}\right\}}{\partial y}-\bar{a}h^{cv}(T^s-T^a) \qquad (2)$$

In this equation ρ^s is the cement clinker density, C_p^s is clinker heat capacity, u_x^s is grate speed, and T^s is clinker temperature of solid at any point, K^s is clinker thermal conductivity, $\bar{a}$ is the convection area factor between the clinker and air, h^{cv} is convective heat transfer coefficient between solid clinker and air, T^a is air temperature at any point in the cooler.

In equation 2 the right hand side first and second terms represent the conduction from the cell in x and y directions respectively. Last term in right hand side represents convective heat transfer between the air and solids. Left hand side terms shows the net energy remained in the cell coming from x and y direction.

As we know that solids don't have any velocity in y direction. So by putting

$$u_y = 0$$

The equation becomes:

$$\frac{\partial(\rho^{s}(1-\varepsilon)u_{x}^{s}c_{p}^{s}T^{s})}{\partial x}=\frac{\partial\left\{(1-\varepsilon)K^{s}\frac{\partial T^{s}}{\partial x}\right\}}{\partial x}+\frac{\partial\left\{(1-\varepsilon)K^{s}\frac{\partial T^{s}}{\partial y}\right\}}{\partial y}-\overline{a}h^{cv}(T^{s}-T^{a}) \qquad (3)$$

This is a partial differential equation, which can be converted into an algebraic equation by integrating the equation 3 over the small control volume ΔV of this subdivision. But we have assumed that the cell is of unit width and there is no change occurs along the width of the cooler. So the volume integral will change to surface integral. Now the equation will be

$$\iint_{S}\left(\frac{\partial(\rho^{s}(1-\varepsilon)u_{x}^{s}c_{p}^{s}T^{s})}{\partial x}\right)dx.dy=\iint_{S}\frac{\partial}{\partial x}\left\{(1-\varepsilon)K^{s}\frac{\partial T^{s}}{\partial x}\right\}dx.dy \\ \iint_{S}\frac{\partial}{\partial y}\left\{(1-\varepsilon)K^{s}\frac{\partial T^{s}}{\partial y}\right\}dx.dy-\iint_{S}\overline{a}h^{cv}(T^{s}-T^{a})dx.dy \qquad (4)$$

In the integration of equation 3 over the control volume the limits will be:
In x direction varies from west cell to the east surface, which are denoted by ‘w’ to ‘e’ respectively and in y direction varies from south surface to the north surface, which are denoted by ‘s’ and ‘n’ respectively.

So after integration and by putting limits we get

$$\left(\rho^{s}(1-\varepsilon)u_{x}^{s}c_{p}^{s}T^{s}\Delta y\right)_{e}-\left(\rho^{s}(1-\varepsilon)u_{x}^{s}c_{p}^{s}T^{s}\Delta y\right)_{w} \\ =\left((1-\varepsilon)K^{s}\frac{\partial T^{s}}{\partial x}\Delta y\right)_{e}-\left((1-\varepsilon)K^{s}\frac{\partial T^{s}}{\partial x}\Delta y\right)_{w} \\ +\left((1-\varepsilon)K^{s}\frac{\partial T^{s}}{\partial y}\Delta x\right)_{n}-\left((1-\varepsilon)K^{s}\frac{\partial T^{s}}{\partial y}\Delta x\right)_{s} \\ -\overline{a}h^{cv}(T_{p}^{s}-T_{p}^{a})\Delta x\Delta y \qquad (5)$$

The subdivisions are very small so we have be assumed that the temperature of the solids throughout the subdivision is equal to the outlet temperature of solids from this cell. Now in this equation by putting the values of T_e , T_w , T_s and T_n in the equation

$T_e = T_P$ (6)

This is because each cell is at a uniform temperature T_p and the outlet temperature from that cell is same as T_p (Taking that each cell is completely mixed)

$$T_w = T_W \tag{7}$$

Similarly we can get this because cell output temperature is same as the cell temperature so T_w will be same as the previous cell temperature, which is T_W.

As we mentioned that each element is very small so that we can replace $\frac{\partial T^s}{\partial x}$ by $\frac{\Delta T^s}{\Delta x}$
By this we will get

$$\begin{aligned}
&\left(\rho^s(1-\varepsilon)u_x^s c_p^s \Delta y(T_P^s)\right) - \left(\rho^s(1-\varepsilon)u_x^s c_p^s \Delta y(T_W^s)\right) \\
&= \left((1-\varepsilon)K^s \Delta y(T_E^s - T_P^s)/\Delta x\right) - \left((1-\varepsilon)K^s \Delta y(T_P^s - T_W^s)/\Delta x\right) \\
&\quad + \left((1-\varepsilon)K^s \Delta x(T_N^s - T_P^s)/\Delta y\right) - \left((1-\varepsilon)K^s \Delta x(T_P^s - T_S^s)/\Delta y\right) \\
&\quad - \bar{a}\, h^{cv}(T_p^s - T_p^a)\Delta x \Delta y
\end{aligned} \tag{8}$$

So now by rearranging the equation in a suitable manner we will get

$$\boxed{a_P^s T_P^s = a_E^s T_E^s + a_W^s T_W^s + a_N^s T_N^s + a_S^s T_S^s + S_u^s} \tag{9}$$

This is a standard format to write a steady state equation for diffusion of a property ϕ. In equation 9 the diffusion of Temperature T at any subdivision P is written in terms of heat flux coming form all the directions and a source term.
In equation 9 the values of the different constants are

$$a_P^s = \left(a_E^s + a_W^s + a_N^s + a_S^s + \bar{a}\, h_P^{cv} \Delta x \Delta y\right) \tag{10}$$

a_P^s is coefficient of temperature of (i,j) subdivision on which we are writing energy balance.

$$a_E^s = \left((1-\varepsilon)K^s \Delta y/\Delta x\right)_E \tag{11}$$

This represents the term of heat flux coming from the east direction to this cell. From the east direction heat transfer is only due to conduction among the solids. In equation 11 there is no term of outgoing heat flux due to solid movement because the temperature of outgoing solids is equal to the cell temperature.

$$a_W^s = \left(\left((1-\varepsilon)K^s \Delta y/\Delta x\right) + \rho^s(1-\varepsilon)u_x^s c_p^s \Delta y\right)_W \tag{12}$$

Here a_W^s represents the term of heat flux coming from the west direction to this cell. From the west direction heat flux is due to conduction among the solids and the heat, which is coming with the solids coming to this cell.

$$a_N^s = \left(\left((1-\varepsilon)K^s \Delta x/\Delta y\right)\right)_N \tag{13}$$

This represents the term of heat flux coming from the north direction to this cell. From the north direction heat transfer is only due to conduction among the solids because solids don't have any motion in this direction.

$$a_S^s = \left(\left((1-\varepsilon)K^s \Delta x/\Delta y\right)\right)_S \tag{14}$$

This represents the term of heat flux coming from the south direction to this cell. From the south direction heat transfer is only due to conduction among the solids because solids don't have any motion in this direction.

$$S_U^s = \overline{a}\, h_P^{cv} \Delta x \Delta y T_P^a \tag{15}$$

This represents the source of heat in the cell. In this case source term is due to heat transfer by convection. But this will be different at different boundary conditions. All properties in all these equations should be calculated at the respective cell temperatures. Boundary conditions at the boundaries of the bed are shown in Figure 3. Radiation was considered only at the top layer of clinker bed. At the right face of the clinker bed we assumed that the heat flux in the X direction is zero. At the entrance of clinker bed we assumed the heat flux in X direction is zero. At the bottom layer of clinker bed the heat flux was assumed to be zero in y direction. Now by using these boundary conditions we can form energy balance equations for each subdivision. In these equations the unknowns are bed and air temperatures.

2.2.3 Mass balance for air

Cooling air is flowing in direction perpendicular to the grate along the y-axis as shown in Figure 4.

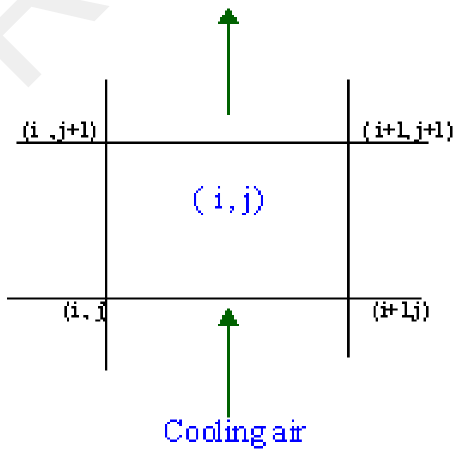


Figure 4. General (i,j)th subdivision for air balance

The mass flow rate of air in the bed region is equal to the inlet mass flow rate of air to the cooler. So the mass balance equation for any subdivision in the bed region will be

$$m^a_{(i,j),in} = m^a_{(i,j),out} = m^a_{in}\left(\frac{\Delta x}{L}\right) \qquad (16)$$

In the freeboard region we have taken uniform mixing of air coming from horizontal direction and vertical direction. So the mass balance equation for air in this region will be

$$m^{aH}_{i,m+1} = (n+1-i)\ m^{aV}_0 \qquad (17)$$

2.2.4 Energy balance for air

We are writing energy balance equations for air in a general (i ,j) subdivision. As shown in **Figure 4** the air is coming at a low temperature taken as T_s^a to this cell. Air is receiving heat by convection from the solids and exiting from the cell at a temperature T_P^a. The cooler is in continuous mode and we are assuming it to be stead. So there will be no accumulation of energy in any subdivision. A general energy balance for air can be written as

$$\frac{\partial(\rho^a \varepsilon u_x^a c_p^a T^a)}{\partial x} + \frac{\partial(\rho^a \varepsilon u_y^a c_p^a T^a)}{\partial y} = \frac{\partial\left\{K^a \varepsilon \frac{\partial T^a}{\partial x}\right\}}{\partial x} + \frac{\partial\left\{K^a \varepsilon \frac{\partial T^a}{\partial y}\right\}}{\partial y} + \bar{a} h^{cv}(T^s - T^a) \qquad (18)$$

In this equation ρ^a is the air density, C_p^a is air heat capacity, u_y^a is air inlet speed, and T^a is air temperature at any point, K is air thermal conductivity, $\bar{a}$ is the convection area factor between the clinker and air, h^{cv} is convective heat transfer coefficient between solid clinkers and air, T^s is solid temperature at any point in the cooler. In equation 18 the left hand side terms represents the net energy input by the air. First two terms in the right hand side are due to conduction between the air layers and the final term is due to the convection between solids and air. As we know that the thermal conductivity of the air is very less and the neighboring cells are at approximately same temperature so the conductive heat transfer among the air layers will be negligible. And we have assumed air to be flowing in plug flow along y direction so the air velocity in x direction will be zero.

$$u_x = 0$$

The equation will be

$$\therefore \frac{\partial(\rho^a u_y^a c_p^a T^a)}{\partial y} = \bar{a} h^{cv}(T^s - T^a) \qquad (19)$$

Similarly by integrating this equation over this control volume ΔV we get

$$\left(\rho^a \varepsilon\ u_y^a c_p^a T^a \Delta x\right)_n - \left(\rho^a \varepsilon\ u_y^a c_p^a T^a \Delta x\right)_s = \bar{a} h^{cv}(T_p^s - T_p^a)\Delta x \Delta y \qquad (20)$$

Now by putting values of T_s^a and T_n^a as
$T_n^a = T_P^a$
$T_s^a = T_S^a$
We will get

$$\left(\rho^a \varepsilon \ u_y^a c_p^a \Delta x T_P^a\right) - \left(\rho^a \varepsilon \ u_y^a c_p^a \Delta x T_S^a)\right) = \overline{a}\ h^{cv} (T_p^s - T_p^a) \Delta x \Delta y \qquad (21)$$

So by rearranging the terms in the equation 21 to get the standard format for the diffusion of air temperature

$$\boldsymbol{a_P^a T_P^a = a_E^a T_E^a + a_W^a T_W^a + a_N^a T_N^a + a_S^a T_S^a + S_u^a} \qquad (22)$$

In this equation the values of the different constants are

$$a_E^a = 0 \qquad (23)$$

This represents that no heat flux is coming to this cell from the east direction. Because air don't have any velocity in this direction and no conduction is present in air.

$$a_W^a = 0 \qquad (24)$$

This represents that no heat flux is coming to this cell from the west direction also. Because air don't have any velocity in this direction and no conduction is present in air.

$$a_N^a = 0 \qquad (25)$$

This represents that no heat flux have the term of T_N. Because we have assumed that the outlet air temperature is equal to the cell temperature and we are not considering any conduction in air.

$$a_S^a = \left(\rho^a \varepsilon \ u_y^a c_p^a \Delta x\right)_S \qquad (26)$$

This contains the heat coming to the cell with air from the south direction.

$$a_P^a = \left((a_E^a + a_W^a + a_N^a + a_S^a) + \overline{a}\ h_P^{cv} \Delta x \Delta y\right) \qquad (27)$$

This is coefficient of air temperature of this cell, which is a function of all other coefficients and the convection term.

$$S_U^a = \overline{a}\ h_P^{cv} \Delta x \Delta y T_P^s \qquad (28)$$

This represents the source of heat in the cell. In this case source term is due to heat transfer by convection. But this source term will be different at different boundary conditions.

All the properties should be calculated at respective cell temperatures for calculation of all these coefficients. Using these general equations we can write energy balance equations for air in each cell. In these equations the unknowns are bed and air temperatures.

So if we calculate the convective heat transfer coefficient between solids and air, then this system of algebraic equations can be solved using any numerical technique for solving a system of equations.

2.3 Model for calculating convective heat transfer coefficient between clinkers and air

Developing accurate models for convective heat transfer coefficient between solids and air is most important because the dominating mode of heat transfer in the cooler is convection. The calculations are based on empirically determined heat transfer coefficient for forced convection in packed bed, through which air moving from bottom to top (in perpendicular direction of the bed) and which consists of individual particles. d. This assumption is reasonable because the grate speed varies from 0.05-0.2 m/sec and the cooling air speed varies from 5-15 m/sec. Extensive data for forced convection for the flow of gases through a packed bed was published by B.W.Gamson, G. Thodos, and O. A. Hougen (1943). And using this data a correlation for CHILTON –COLBURN factor was obtained by Stewart, who did extensive study of packed beds.

$$J_H = 2.19\,\mathrm{Re}^{-2/3} + 0.78\,\mathrm{Re}^{-0.381} \qquad (29)$$

In equation 29 J_H represents the Chilton-Colburn factor and Re represents Reynolds number for the clinker particles. Which are defined as

$$J_H = \frac{h_{cv}}{C_P^a \rho^a v_p^a}\left(\frac{C_P^a \mu^a}{k^a}\right) \qquad (30)$$

$$\mathrm{Re} = \frac{D_P^s \rho^a v_p^a}{(1-\varepsilon)\mu^a \phi^s} \qquad (31)$$

In these equations h_{cv} is convective heat transfer coefficient between clinkers and the air, C_P^a is heat capacity of air, μ^a is viscosity of air, k^a thermal conductivity of air, ρ^a is density of air, v_p^a is the velocity of the air at that point, D_P^s is clinker diameter, ε is the porosity of the bed, ϕ^s is the sphericty of the clinker particles which is 1 in case of spherical particles. All the physical properties should be calculated at the film temperature $T_f = (T_s + T_a)/2$.

In these equations ρ^a and v_p^a always come together so we don't have to calculate air velocity at each and every point because the term $\rho^a v_p^a$ is basically the mass flux rate of air which is constant through out the bed. This shows that this heat transfer depends on the particle size, shape, porosity of the bed, mass flux of air through the bed, and the air properties, which should be calculated at the film temperature only. Based on this heat transfer coefficient we can calculate convective heat transfer between the hot clinkers and the cooling air.

2.4 Balance equations for computational modeling

To solve the mass and energy balance equations using a computer model we have to form equations for all the nodes separately. Earlier we have shown the equations of mass and energy balance for solids and air in a grate cooler. The equations for mass balance are directly valid for the computer model but for the energy balance the equations have to be modified suitably. Therefore, to convert the energy equations shown above in section 2.2.2 and 2.2.4 for a computer program by taking a (i,j) Cell

Replace the subscripts
'P' by (i, j)
'E' by (i + 1 , j)
'W' by (i –1 , j)
'N' by (i , j + 1)
'S' by (i , j -1)

Now by putting appropriate boundary conditions we can write mass and energy balance equations for all the subdivisions.

2.4.1 Energy equations for solids

Case: 1 i = 2 to (n-1) & j = 2 to (m-1)

This is a general subdivision. In this subdivision conduction from all the sides is present. At this cell we have not considered any radiation from the solids because this solid layer will be always surrounded with other layers of solids. Therefore, the temperature difference between the cell temperature and surrounding temperature will be very less. So we the radiation term will be negligible at this layer of solids.

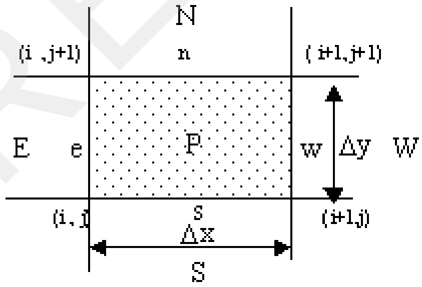


Figure 5. A general computational cell

So for this case the coefficient values in equation 9 will be

$$a_P^s = \left(a_E^s + a_W^s + a_N^s + a_S^s + \bar{a} h_P^{cv} \Delta x \Delta y\right)$$
$$a_E^s = \left((1-\varepsilon) K^s \Delta y / \Delta x\right)_E$$
$$a_W^s = \left(\left((1-\varepsilon) K^s \Delta y / \Delta x\right) + \ \rho^s (1-\varepsilon) u_x^s c_p^s \Delta y\right)_W$$
$$a_N^s = \left(\left((1-\varepsilon) K^s \Delta x / \Delta y\right)\right)_N$$
$$a_S^s = \left(\left((1-\varepsilon) K^s \Delta x / \Delta y\right)\right)_S$$

$$S_U^s = \overline{a}\, h_P^{cv} \Delta x \Delta y T_P^a$$

Case: 2 **i = 1 & j = 1**

This is the lower left corner of the grid, formed to solve the energy balance in the grate cooler. At this cell there will be no conduction from the west side and from south side because there are no solids in these two directions. And at this point the temperature of solids coming from the west side is known so T_w will not be a variable at this point and the energy inlet from the west side will behave as a source term in the equation. So for this case the coefficient values in equation 9 will be

$$a_E^s = \left((1-\varepsilon)K^s \Delta y / \Delta x\right)_E$$
$$a_W^s = 0$$
$$a_N^s = \left(\left((1-\varepsilon)K^s \Delta x / \Delta y\right)\right)_N$$
$$a_S^s = 0$$
$$a_P^s = \left(a_E^s + a_N^s + \left(\rho^s (1-\varepsilon) u_x^s c_p^s \Delta y\right)_E + \overline{a}\, h_P^{cv} \Delta x \Delta y\right)$$
$$S_U^s = \overline{a}\, h_P^{cv} \Delta x \Delta y T_P^a + \left(\rho^s (1-\varepsilon) u_x^s c_p^s \Delta y T_{in}^s\right)_{in}$$

Case: 3 **i = 2 to (n-1) & j = 1**

This is the bottom layer of the solids, which is in direct contact with the grate. At this row of cells there will be no conduction from south side since there are no solids in the south direction. So for this case the coefficient values in equation 9 will be

$$a_E^s = \left((1-\varepsilon)K^s \Delta y / \Delta x\right)_E$$
$$a_W^s = \left(\left((1-\varepsilon)K^s \Delta y / \Delta x\right) + \rho^s (1-\varepsilon) u_x^s c_p^s \Delta y\right)_W$$
$$a_N^s = \left((1-\varepsilon)K^s \Delta x / \Delta y\right)_N$$
$$a_S^s = 0$$
$$a_P^s = \left(a_E^s + a_W^s + a_N^s + \overline{a}\, h_P^{cv} \Delta x \Delta y\right)$$
$$S_U^s = \overline{a}\, h_P^{cv} \Delta x \Delta y T_P^a$$

Case: 4 **i = n & j = 1**

This is the lower right corner of the domain. At this cell there will not be any conduction from east as well as south direction, since there are no solids present in these directions. So the heat flux from the south direction will be completely zero. So for this case the coefficient values in equation 9 will be

$$a_E^s = \left(-\rho^s (1-\varepsilon) u_x^s c_p^s \Delta y\right)_E$$
$$a_W^s = \left(\left((1-\varepsilon)K^s \Delta y / \Delta x\right) + \rho^s (1-\varepsilon) u_x^s c_p^s \Delta y\right)_W$$
$$a_N^s = \left((1-\varepsilon)K^s \Delta x / \Delta y\right)_N$$
$$a_S^s = 0$$

$$a_P^s = \left(a_W^s + a_N^s + \overline{a}\, h_P^{cv} \Delta x \Delta y\right)$$
$$S_U^s = \overline{a}\, h_P^{cv} \Delta x \Delta y T_P^a$$

Case: 5 i = n & j = 2 to(m-1)

This is the extreme right column of the domain from which directly solids are coming out. At this column of the cells there will be no conduction in east direction. So for this case the coefficient values in equation 9 will be

$$a_E^s = \left(-\rho^s (1-\varepsilon) u_x^s c_p^s \Delta y\right)_E$$
$$a_W^s = \left(\left((1-\varepsilon) K^s \Delta y / \Delta x\right) + \rho^s (1-\varepsilon) u_x^s c_p^s \Delta y\right)_W$$
$$a_N^s = \left((1-\varepsilon) K^s \Delta x / \Delta y\right)_N$$
$$a_S^s = \left((1-\varepsilon) K^s \Delta x / \Delta y\right)_S$$
$$a_P^s = \left(a_W^s + a_N^s + a_S^s + \overline{a}\, h_P^{cv} \Delta x \Delta y\right)$$
$$S_U^s = \overline{a}\, h_P^{cv} \Delta x \Delta y T_P^a$$

Case: 6 i = 1 & j = 2 to (m-1)

This is the extreme left column of the domain from which directly hot clinkers are coming from the rotary kiln to the cooler. At this column of cells there will not be any conduction from west direction and the solid inlet temperature is known at this column so the heat inlet by the solids to these cells will behave as source term. So for this case the coefficient values in equation 9 will be

$$a_E^s = \left((1-\varepsilon) K^s \Delta y / \Delta x\right)_E$$
$$a_W^s = 0$$
$$a_N^s = \left((1-\varepsilon) K^s \Delta x / \Delta y\right)_N$$
$$a_S^s = \left((1-\varepsilon) K^s \Delta x / \Delta y\right)_S$$
$$a_P^s = \left(a_E^s + a_N^s + a_S^s + \left(\rho^s (1-\varepsilon) u_x^s c_p^s \Delta y\right)_E + \overline{a}\, h_P^{cv} \Delta x \Delta y\right)$$
$$S_U^s = \overline{a}\, h_P^{cv} \Delta x \Delta y T_P^a + \left(\rho^s (1-\varepsilon) u_x^s c_p^s \Delta y T_{in}^s\right)$$

Case: 7 i = 1 & j = m

This is the top left corner of the domain from which directly solids are coming in and are exposed to the free board region. At this cell there will not be any conduction from west as well as north direction and the radiation at this cell will be high because solids are exposed to the free board region. Therefore, for this cell we have considered radiation from the solids present at this cell. So for this case the coefficient values in equation 9 will be

$$a_E^s = \left((1-\varepsilon) K^s \Delta y / \Delta x\right)_E$$
$$a_W^s = 0$$
$$a_N^s = 0$$

$$a_S^s = \left((1-\varepsilon)K^s \Delta x / \Delta y\right)_S$$
$$a_P^s = \left(a_E^s + a_S^s + \left(\rho^s(1-\varepsilon)u_x^s c_p^s \Delta y\right)_E + \overline{a}\, h_P^{cv} \Delta x \Delta y + \sigma\varepsilon_s \Delta x (1-\varepsilon) T^{s3}\right)$$
$$S_U^s = \overline{a}\, h_P^{cv} \Delta x \Delta y T_P^a + \left(\rho^s(1-\varepsilon)u_x^s c_p^s \Delta y T_{in}^s\right) + \sigma\varepsilon_s \Delta x (1-\varepsilon) T^{a4}$$

Case: 8 i *= 2 to (n-1) & j = m*

This is the top row of the domain at which solids are in contact of free board region. At this row there will not be any conduction from north direction. But there will be radiation from the hot clinkers to air. So for this case the coefficient values in equation 9 will be

$$a_E^s = \left((1-\varepsilon)K^s \Delta y / \Delta x\right)_E$$
$$a_W^s = \left(\left((1-\varepsilon)K^s \Delta y / \Delta x\right) + \rho^s(1-\varepsilon)u_x^s c_p^s \Delta y\right)_W$$
$$a_N^s = 0$$
$$a_S^s = \left((1-\varepsilon)K^s \Delta x / \Delta y\right)_S$$
$$a_P^s = \left(a_E^s + a_W^s + a_S^s + \overline{a}\, h_P^{cv} \Delta x \Delta y + \sigma\varepsilon_s \Delta x (1-\varepsilon) T^{s3}\right)$$
$$S_U^s = \overline{a}\, h_P^{cv} \Delta x \Delta y T_P^a + \sigma\varepsilon_s \Delta x (1-\varepsilon) T^{a4}$$

Case: 9 i = n & j = m

This is the top left corner of the domain from which directly solids are coming out and are exposed to the free board region. At this cell there will not be any conduction from east as well as north direction and the radiation at this cell will be high because solids are exposed to the free board region. Therefore, for this cell we have considered radiation from the solids present at this cell. So for this case the coefficient values in equation 9 will be

$$a_E^s = 0$$
$$a_W^s = \left(\left((1-\varepsilon)K^s \Delta y / \Delta x\right) + \rho^s(1-\varepsilon)u_x^s c_p^s \Delta y\right)_W$$
$$a_N^s = 0$$
$$a_S^s = \left((1-\varepsilon)K^s \Delta x / \Delta y\right)_S$$
$$a_P^s = \left(a_W^s + a_S^s + \overline{a}\, h_P^{cv} \Delta x \Delta y + \sigma\varepsilon_s \Delta x T^{s3}\right)$$
$$S_U^s = \overline{a}\, h_P^{cv} \Delta x \Delta y T_P^a + \sigma\varepsilon_s \Delta x T^{a4}$$

2.4.2 Model equations for air

Case: 1 i = 1 to n & j = 2 to (m)

This is general cell, which is always surrounded with the other cells from all directions. The coefficient in equation 22 for this case will be

$$a_E^a = 0$$
$$a_W^a = 0$$

$a_N^a = 0$

$a_S^a = \left(\rho^a \varepsilon\, u_y^a c_p^a \Delta x T^a\right)$

$a_P^a = \left((a_E^a + a_W^a + a_N^a + a_S^a) + \overline{a}\, h_P^{cv} \Delta x \Delta y\right)$

$S_U^a = \overline{a}\, h_P^{cv} \Delta x \Delta y T_P^s + \left(\rho^a \varepsilon\, u_y^a c_p^a \Delta x T^a\right)_{in}$

All the properties should be calculated at respective cell temperatures for calculation of all these coefficients.

Case: 2 j = 1 & i = 1 to n

This is bottom layer of the domain at which cooling air is entering into the cooler. The inlet temperature of the air inlet will be known so at this layer the energy inlet to the cell by air will behave as a source term for the solving purpose. The coefficient in equation 22 for this case will be

$a_E^a = 0$

$a_W^a = 0$

$a_N^a = 0$

$a_S^a = 0$

$a_P^a = \left((a_E^a + a_W^a + a_N^a + a_S^a) + \overline{a}\, h_P^{cv} \Delta x \Delta y\right)$

$S_U^a = \overline{a}\, h_P^{cv} \Delta x \Delta y T_P^s + \left(\rho^a \varepsilon\, u_y^a c_p^a \Delta x T^a\right)_{in}$

All the properties should be calculated at respective cell temperatures for calculation of all these coefficients.

Case: 3 j = (m+1) & i = 1 to n

In this region only air is present thus this is called free board region. Air coming from vertical direction and the horizontal direction mixes well and goes to next cell moving as in horizontal direction and some energy comes from the solid top surface radiation also. So energy balance for any (i,m+1)th cell is

$$m_{i,m}^{aV} C_{P(i,m)}^a T_{i,m}^a + m_{i+1,m+1}^{aH} C_{P(i+1,m+1)}^a T_{i+1,m+1}^a + \sigma \varepsilon_s \Delta x (1-\varepsilon)\left[T_{(i,m)}^{s4} - T_{(i,m+1)}^{a4}\right] = m_{i,m+1}^{aH} C_{P(i,m+1)}^a T_{i,m+1}^a \qquad (32)$$

In this equation $m_{i,m}^{aV}$ is mass flow rate of air coming out vertically from a cell in bed region, $m_{i+1,m+1}^{aH}$ is mass flow rate of air coming horizontally from the previous cell in the free board region, ε_s in the emissivity of solids.

2.5 Solving procedure for model equations

The system of equations formed above was solved using VISUAL FORTRAN code. In this system we have (m+1)n unknown air temperatures and (m)(n) unknown solid temperatures. We have these many numbers of equations also. In this system of equations all the terms are linear except the radiation term. So this can be solved using multidimensional Newton raphson method directly. But the operation counts for this method are very high and this method is generally used for highly non-linear systems. But in our case the non-linearity is only at one boundary so we are not going by this method. So to solve the system we are making the radiation term linear. This can be used when we solve the system iteratively. Now we have a system of linear algebraic equations, which can be solved using direct or indirect (iterative) methods. Some of the direct methods are Gauss elimination, LU decomposition, and Cramer's rule matrix inversion. But operational counts for these methods are very high. As we can see form the equations that the air temperature of any cell is only dependent on two more temperatures represents a linear system. Solid temperature of a cell is dependent on 4 more temperatures that is similar to two dimensional system. This represents that if we solve air and solids separately then the air system forms a tri-diagonal system and the solids form a penta-diagonal system. So this system can be solved by tri-diagonal matrix algorithm (TDMA).

2.5.1 Tri-diagonal matrix algorithm

This is a technique for rapidly solving tri-diagonal system developed by Thomas (1949), which is also called as Thomas algorithm. Consider a system of equations that has a tri-diagonal form

$$D_1\phi_1 - \alpha_1\phi_1 = C_1$$
$$-\beta_2\phi_1 + D_2\phi_2 - \alpha_2\phi_3 = C_2$$
$$-\beta_3\phi_2 + D_3\phi_3 - \alpha_3\phi_4 = C_3$$
……………………………
$$-\beta_n\phi_{n-1} + D_n\phi_n = C_n$$

This system of equations can be solved by rearranging terms and then by forward or back substitution. We are using backward substitution to solve the system. The general form of recurrence relationship for back substitution is

$$\phi_j = A_j\phi_{j+1} + C'_j$$

Where

$$A_j = \frac{\alpha_j}{D_j - \beta_j A_{j-1}}$$

$$C_j = \frac{\beta_j C'_{j-1} + C_j}{D_j - \beta_j A_{j-1}}$$

So by this procedure we can we can solve any tri-diagonal system very rapidly. This is a direct method for one-dimensional systems and an indirect method for two-dimensional problems. In a two dimensional problem this can be applied iteratively, in a line-by-line fashion. Consider a general two-dimensional discretised equation of form

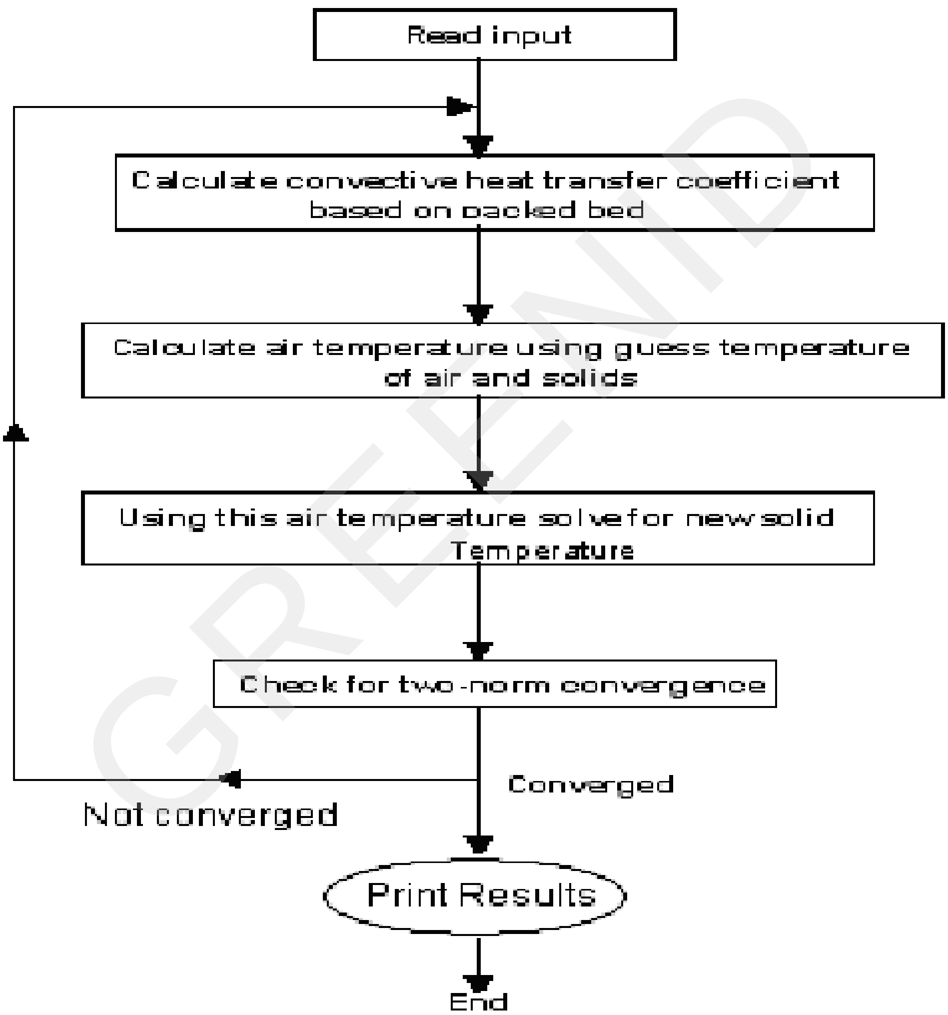
$$\boldsymbol{a_P^a T_P^a = a_E^a T_E^a + a_W^a T_W^a + a_N^a T_N^a + a_S^a T_S^a + S_u^a}$$

To solve the system we need to have a tri-diagonal system. So the TDMA technique is applied line by line in the domain. For example to solve along north-south (n-s) lines we will assume east and west direction to be known. Therefore the equation can be rearranged in this form

$$-a_S^a T_S^a + a_P^a T_P^a - a_N^a T_N^a = a_E^a T_E^a + a_W^a T_W^a + S_u^a$$

The right hand side is known because we have already assumed the east and west direction temperatures. So this is a tri-diagonal system now, which can be solved using TDMA technique. Subsequently the calculation is moved to the next north-south line. After sweeping whole domain along north-south direction now we can sweep along east west direction because the temperature of north-south direction is known. Like this we keep on sweeping until the values of all the variables converge.

2.5.2 Computational model



"**Figure 6.** (Flow diagram for computer simulation)"

The programming code was developed using Visual Fortran. We are solving the equations using iterative procedure. In the code firstly we read operating parameter for cooler and the initial guess for the solid and air temperature from the input files. Now at this guess temperature we calculate air properties and the convective heat transfer coefficient between solids and air. Then we form tri-diagonal system for air along north-south line assuming the solids temperature to be equal to the initial guess. This system of equations was solved using TDMA technique. Similarly we sweep for whole domain. At this new air temperature calculate air properties and the convective heat transfer coefficient. Using the air temperature and east-west direction solid temperature as guess solve for solids first along the north south direction. Sweep along this direction over whole domain. Now improve the initial guess temperature for further calculations using under relaxation technique. So the new guess temperature of solids and air will be

$$T_{new}^{s} = T_{old}^{s} + \alpha_T T_{new}^{s} \quad (33)$$

where α_T is the under-relaxation factor. This under relaxation parameter can be varied from 0 to 1. If we select α_T equal to zero then it will be same as any normal scheme. This is used to make the convergence faster and if at α_T = 0 the system is diverging then using this method we can make the system convergent. Now this temperature is used as guess for air calculation and the procedure is repeated until the calculated parameters satisfy the two norm convergence criteria. Then all the results were printed into separate files for air and solids. By changing operating parameters and number of subdivisions several numerical simulations were carried out.

3 Results and discussion

We carried out several simulations by changing operational parameters for the cooler to find the effect of each parameter on the performance of cooler. Some of the simulation results are discussed below.

Case: 1

In this case the **temperature variation of cement clinker along the length of cooler at various heights** is discussed and shown in Figure 7. For this case the grate velocity was taken as 0.1 m/s, mass flow rates of cement clinker and air were taken as 33 kg/s and 25 kg/s respectively. The length of cooler was assumed to be 11 m. The air and cement clinker inlet temperatures were taken as 300 K and 1673 K respectively. Iterations were carried out for these values of operational parameters and the result is shown in Figure 7.

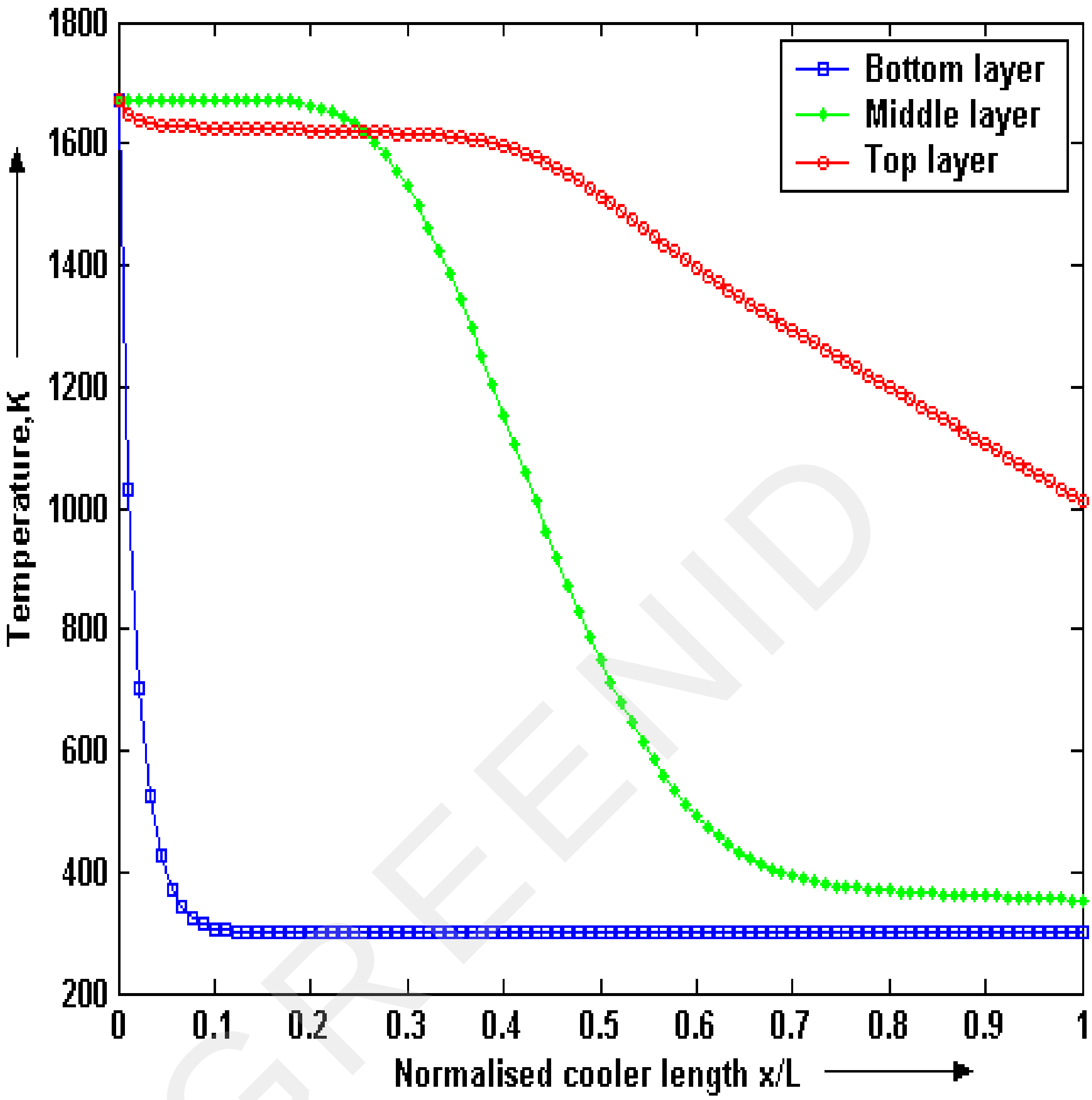


Figure: 7 "Clinker temperature variation against cooler length at various heights"

As we can see from Figure 7 that at the initial length the heat transfer is more at the bottom layers of clinker bed compare to the upper layers of clinker bed. This is because as the air moves upward the temperature of air increases and after a certain bed height it reaches to the solid temperature. After this no more heat transfer can take place. So according to this the temperature of top layer of solids should be maximum.

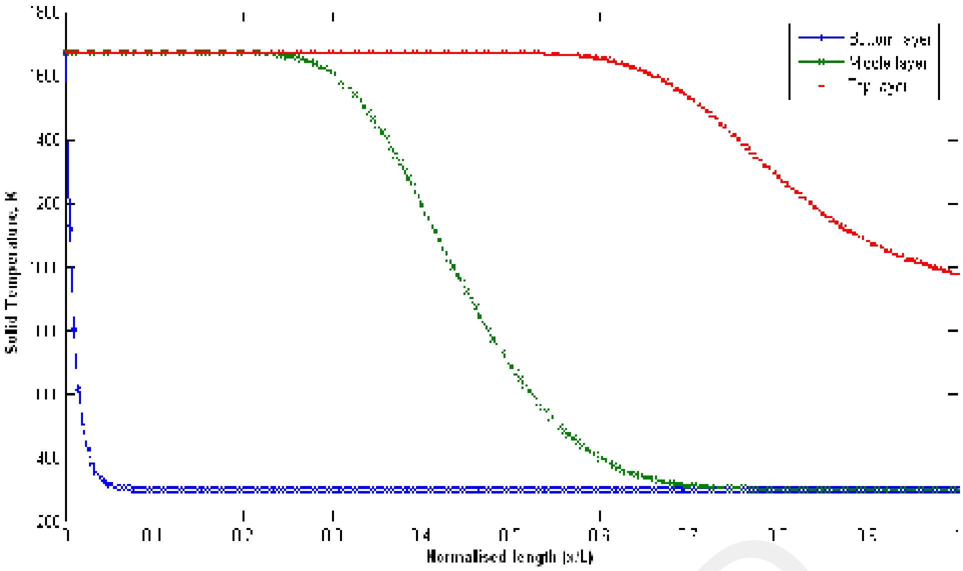


Figure: 8 "Clinker temperature variation against cooler length at various heights without radiation "

This can be seen from Figure 8 that when we consider no radiation from solids the temperature of top layers is always higher than the temperatures of other layers. But when we consider radiation from the solids we can see from the Figure 7 that at the initial length of cooler top layer temperature slightly less than the middle layer temperature. The concept behind this is that in the bed region the radiation will be negligible and the significant radiation occurs only at the top layer of clinker because the solids at that layer are in contact with air of free board region. The temperature of air in the free board region is much less as compare to clinker temperature. Due to radiation solid temperature at this layer decreases.

Now as move along the length of cooler we observe that the heat transfer is increasing at the top layers of clinker and decreasing at the bottom layers of clinker. This is because, after a certain length the bottom layers of solids has reached at a temperature equal to the inlet temperature of air. So no more heat transfer heat transfer can take place at these layers. Now the air, which goes to top layers, will be at lower temperature so the maximum heat transfer will take place in the upper part of the bed. Because of this there was a significant difference in outlet temperatures of top and bottom layers of clinker.

Case: 2

In this case temperature **variation of air along the length of cooler at various heights** is discussed and shown in Figure 9. The grate velocity was taken as 0.1 m/s. The mass flow rates of cement clinker and air were taken as **33 kg/s** and **25 kg/s** respectively. The length of cooler was assumed to be **11 m** and the air and cement clinker inlet temperatures were taken as **300 K** and **1673 K** respectively. Iterations were carried out for these values of operational parameters and the result is shown in Figure 9.

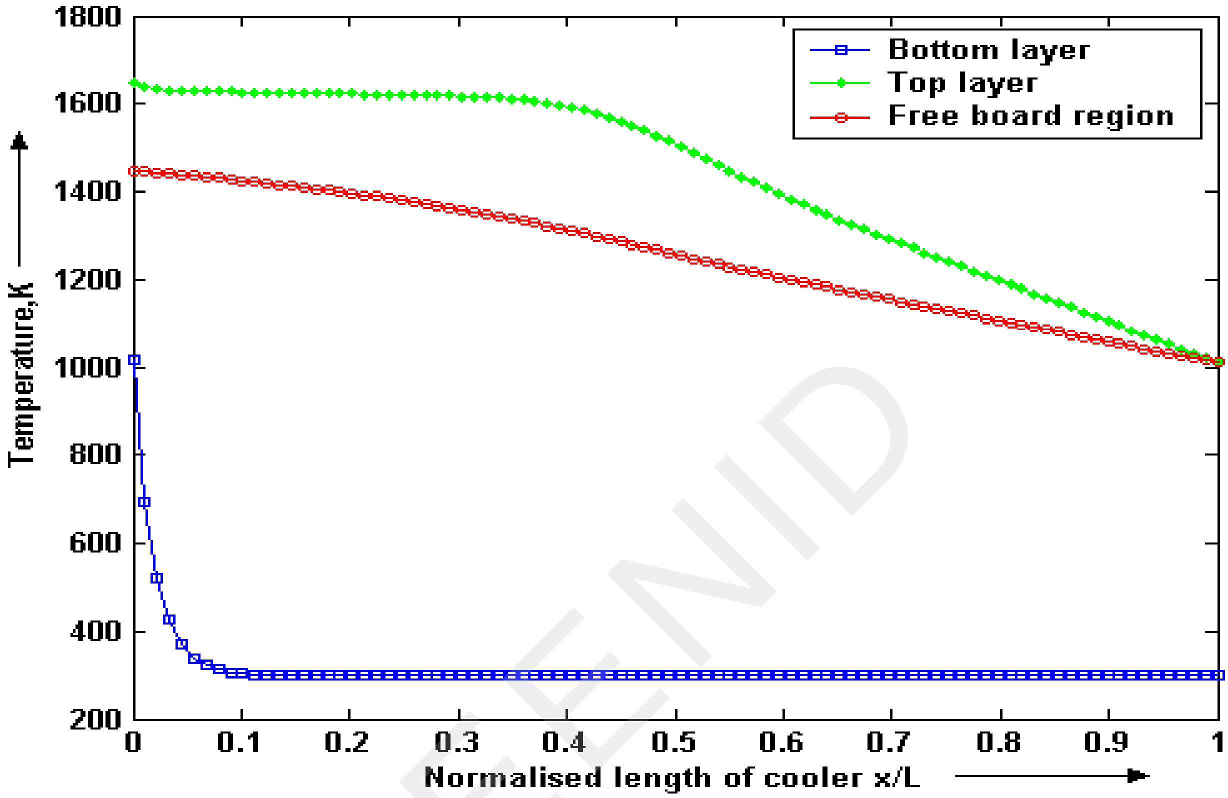


Figure 9 "The temperature variation of air along the length of cooler"

As we can see from Figure 9 that at the initial length the heat transfer is more at the bottom layers of air compare to the upper layers of air. This is because as the air moves upward the temperature of air increases and after a certain bed height it reaches to the solid temperature and no more heat transfer can take place. So according to this the temperature of top layer of air should be maximum. This can be seen from Figure 9 that in the free board region the temperature of air is less than the temperature of top layer of air. Because we are considering the mixing of air in free board region and due to mixing the temperature decreases.

Now as move along the length of cooler we observe that the heat transfer is increasing at the top layers of air and decreasing at the bottom layers of air. This is because, after a certain length the bottom layers of solids has reached at to the inlet temperature of air. So no more heat transfer heat transfer can take place at these layers. Now the air, which goes to top layers, will be at lower temperature so the maximum heat transfer will take place in the upper part of the bed. Because of this there was a significant difference in outlet temperatures of top and bottom layers of air.

Case: 3

In this case temperature **variation of air along the length of cooler at various heights** is discussed and shown in Figure 10. The grate velocity was taken as **0.1 m/s**. The mass flow rates of cement clinker and air were taken as **33 kg/s** and **25 kg/s** respectively. The length of cooler was assumed to be **11 m** and the air and cement clinker inlet temperatures were taken as **300 K** and **1673 K** respectively. Iterations were carried out for these values of operational parameters and the result is shown in Figure 10.

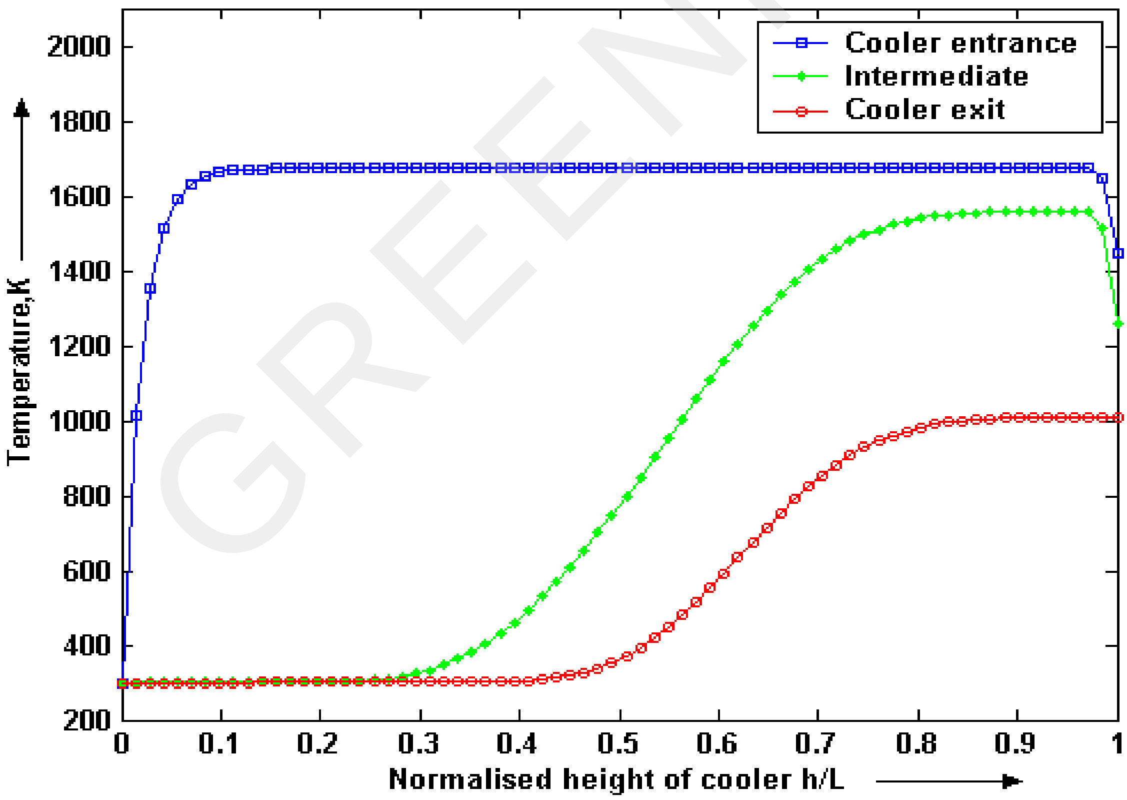


Fig 10 "The temperature varition of air along the height at various

As we can see from Figure 10 that at the initial height the heat transfer is more at the cooler entrance layers of air compare to the cooler exit layers of air. This is because as the solid moves along the length the temperature of solid decreases and after a certain length it reaches to very close to the air temperature. Therefore no more heat transfer can take place at this place.

Now as move along the height of cooler we observe that the heat transfer is increasing at the cooler exit layers of air and decreasing at the cooler entrance of air. This is because, after a certain height the temperature of cooler entrance air has reached at a temperature equal to the inlet temperature of solid. So no more heat transfer heat transfer can take place at these layers. Now the solid, which goes to cooler exit layers, will be at high temperature. So the maximum heat transfer will take place in this part of region.

This can be seen from Figure 10 as we move along the height we reach to the free board region and in this region the temperature of air is less than the temperature of the top layers of air. The explanation is already given in last Figure 10.

Case: 4

As we have seen the temperature variation of cement clinker and air along the length of cooler at different heights. Here in this case we are going to discuss the clinker and air **temperature variation along the length with mass flow rate of solid**. The Figure 11 shows the average caloric temperature variation of clinker and Figure 12 shows the temperature variation of air in free board region along the length of cooler at different mass flow rate of clinker. The grate velocity was taken as **0.1 m/s.** The mass flow rate of air was taken as **25 kg/s**. The length of cooler was assumed to be **11 m** and the air and cement clinker inlet temperatures were taken as **300 K** and **1673 K** respectively. Iterations were carried out for these values of operational parameters and the results are shown in Figure 11 and Figure 12.

From Figure 11 we can see that as we increase the mass flow rates of solid the temperature of solids increases. On the other hand in Figure 12 we can see that as we increases the mass flow rate there is no variation of air temperature with mass flow rate of solid. This is because of as we increases the solid mass flow rate the heat input increases but there is no increment in heat transfer between solid and air. Therefore the air doesn't get any extra amount of heat from solid and therefore the air temperature remains constant with mass flow rate of solid. But as the heat input is increasing the solid temperature also increases.

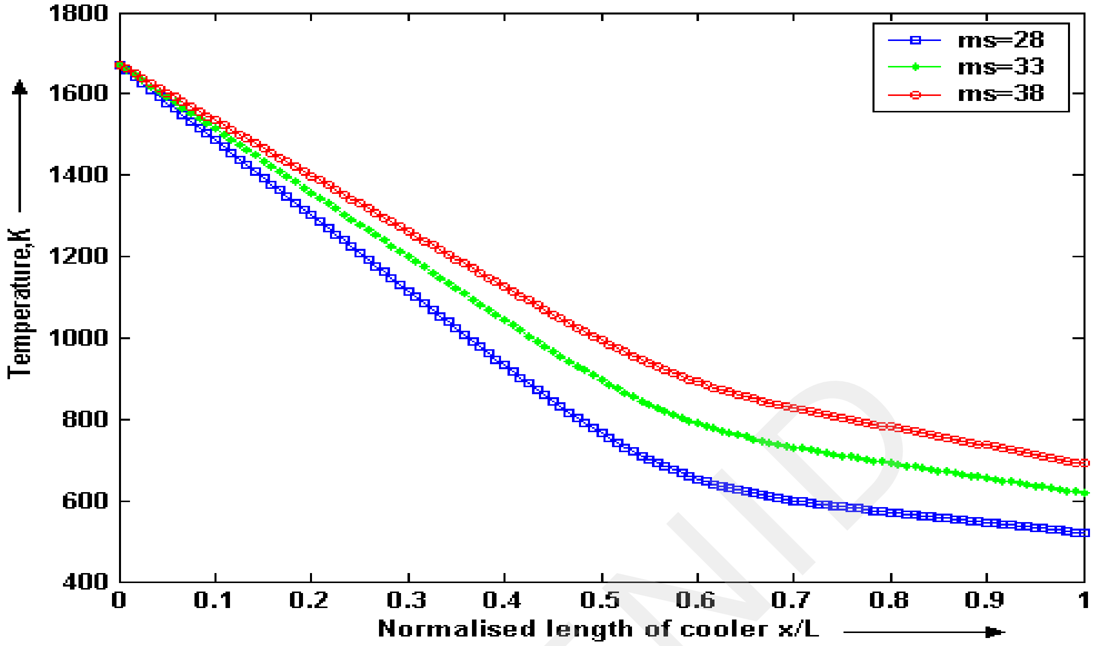


Figure. 11 “variation of clinker temperature along the length of cooler at different mass flow rate of solid”

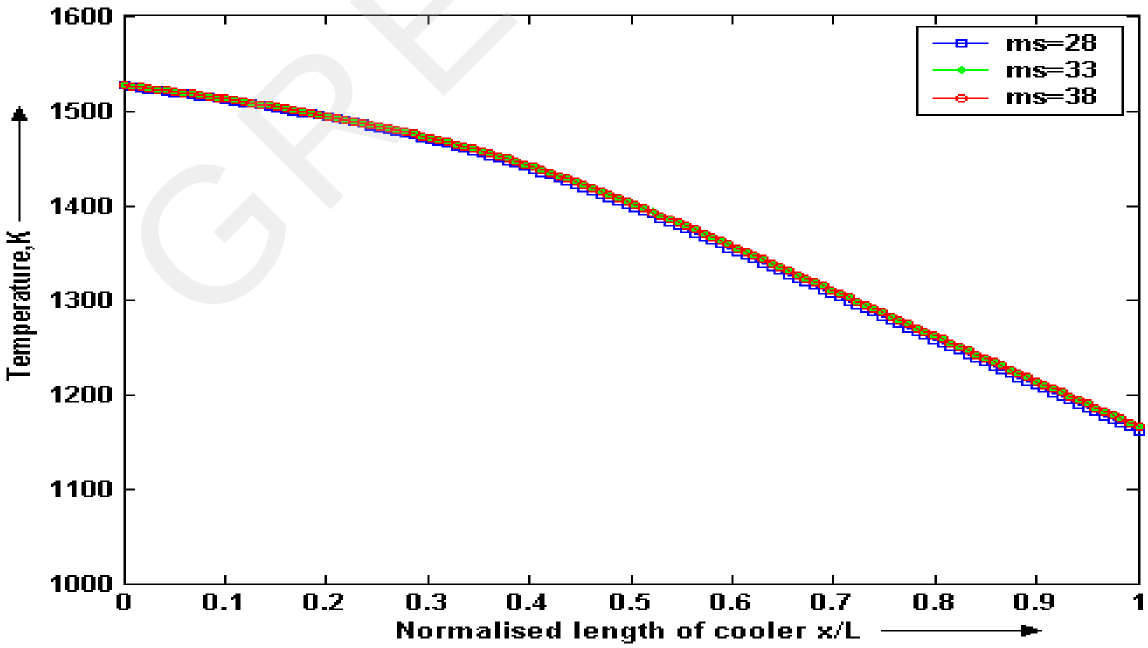


Figure. 12 “Variation of air temperature in free board region along the length of cooler at different mass flow rate of solid”

From these graphs we reach to a conclusion that as we increases the mass flow rate the air temperature doesn't increases and solid temperature increases. But the main task of cooler is to cool the cement clinker to the lowest possible temperature and in the same time the air should be preheated to a temperature level such that we need the lowest fuel of energy for the burning process in rotary kiln. Therefore we have to find out an optimum value of mass flow rate of solid so that the recovery of energy is maximum in the cooler and the plant output is also reasonable. Because as we decrease clinker mass flow rate the output from the plant will decrease.

Case: 5

As we have seen the average caloric temperature variation of cement clinker and air in free board region along the length of cooler with mass flow rate of solid. Now we are going to discuss the variation of average caloric temperature of **clinker and air temperature in free board region along the length of cooler at different mass flow rates of air**.

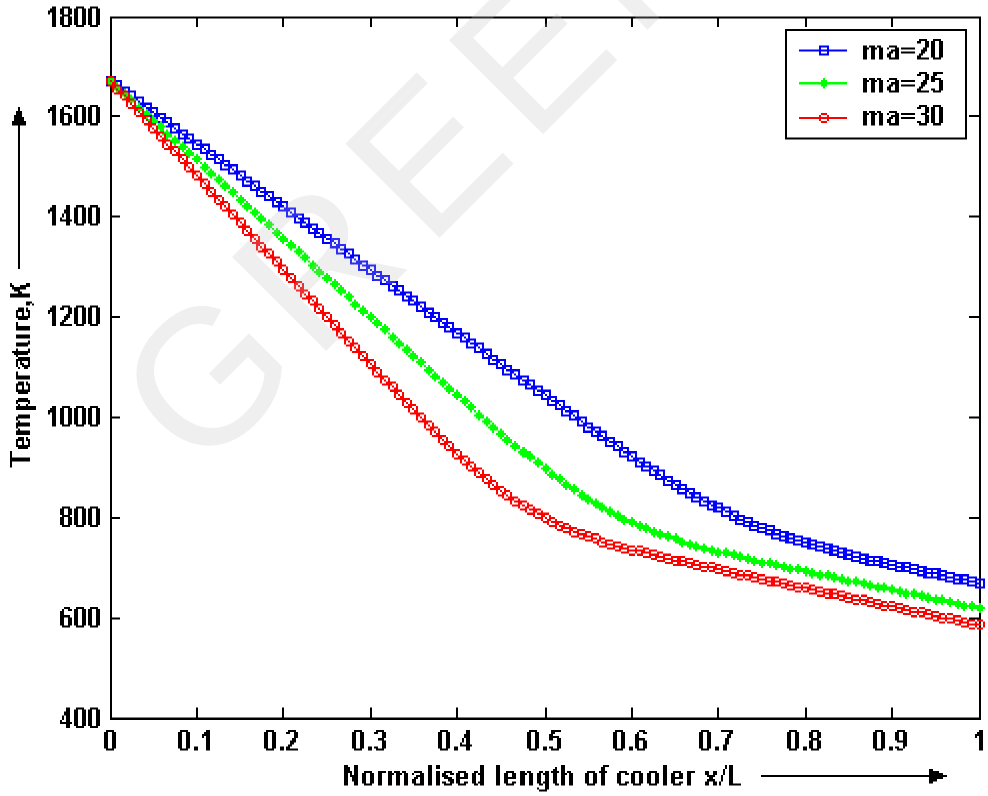


Figure. 13 "Variation of average caloric temperature of the clinker along the length of cooler at different mass flow rate of air"

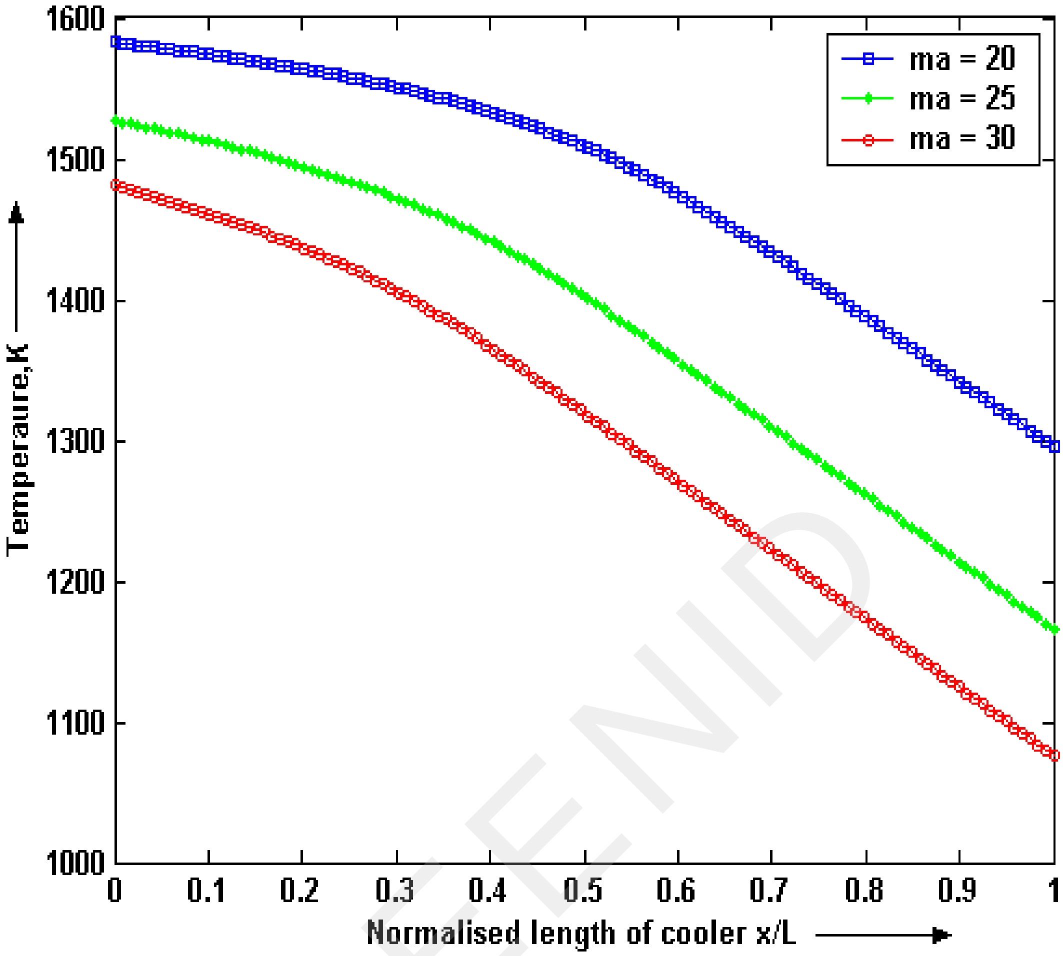


Figure . 14 “Variation of average caloric temperature of the clinker along the length of cooler at different mass flow rate of air”

The Figure 13 shows the average caloric temperature variation of clinker and Figure 14 shows the temperature variation of air in free board region along the length of cooler at different mass flow rates of air. The grate velocity was taken as **0.1 m/s.** The mass flow rate of solid was taken as **33 kg/s**. The length of cooler was assumed to be **11 m** and the air and cement clinker inlet temperatures were taken as **300 K** and **1673 K** respectively. Iterations were carried out on these values of operational parameters and the result is shown in Figure 13 and 14.

Now as we can see from Figure 13 that as we increase the mass flow rates of air the outlet temperature of solid decreases. This represents that we are able to recover more energy from the solids. On the other hand in Figure 14 we can see that with the increase in air mass flow rate the outlet temperature of air decreases. By this we can see that as we increase the air mass flow rate we are able to recover more heat from the solids. But on the other hand the air temperature is decreasing. So we need to find out the optimum mass flow rate of air for which energy recovery is maximum and the mass flow rate of air and its temperature is suitable for coal burning in rotary kiln and calciner.

Case: 6

As we have seen the average caloric temperature variation of cement clinker and air temperature variation in free board region along the length of cooler with mass flow rate of solid and air. Now we are going to discuss the variation of average caloric temperature **of clinker and air temperature variation in free board region with grate speed**.

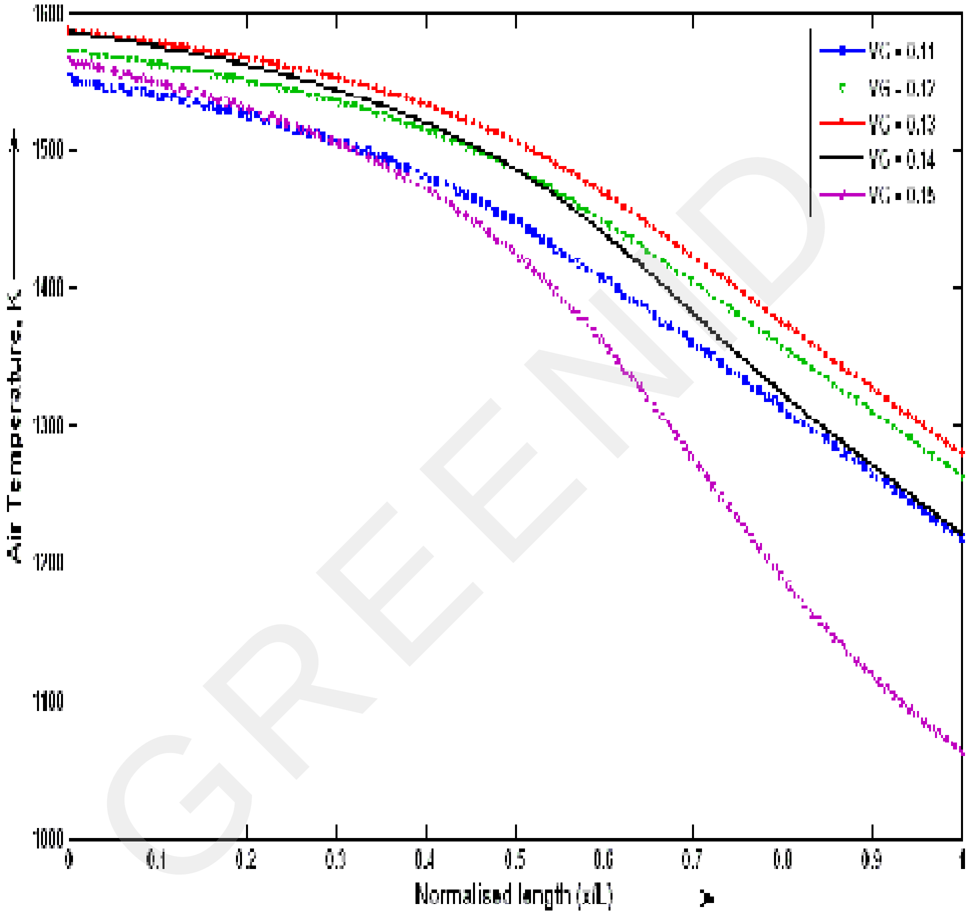


Figure . 15 "Variation of air temperature in free board region along the length of cooler at different grate speeds"

The Figure 15 shows the temperature variation of air in free board region along the length of cooler at different grate speeds. The mass flow rate of solid was taken as **33 kg/s**. The length of cooler was assumed to be **11 m** and the air and cement clinker inlet temperatures were taken as **300 K** and **1673 K** respectively. Iterations were carried out at these values of operational parameters and the result is shown in Figure 15.

From the figure we can see that as we increase grate speed first the air outlet temperature increases with grate speed and after a value of grate speed (~ 0.13m/s) it starts decreasing. The region behind this is that as we increase grate speed the residence time of solids will decrease because of this the heat transfer will decrease. On the other hand as grate speed increases the solid bed height will decrease so the rate of heat transfer will increase. So because of these two effects at a certain velocity the heat transfer will be maximum. For this case the optimum grate speed is around 0.13 m/sec.

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NOMENCLATURE USED IN THE REPORT

ρ^s = Density of cement clinker (solid) (kg/m^3)
u_x^s = Velocity of cement clinker in x-direction (m/s)
c_p^s = Specific heat capacity of cement clinker (kJ/kgK)
ε = Porosity of clinker bed
K^s = Thermal conductivity of cement clinker (W/mK)
h^{cv} = Conductive heat transfer coefficient between air and cement clinker (W/m^{2}K)
$\overline{a}$ = Convection area factor between air and cement clinker
T^s = Temperature of cement clinker in any subdivision (K)
T^a = Temperature of air in any subdivision (K)
T_P^s = Temperature of cement clinker in the (i, j) subdivision (K)
T_W^s = Temperature of cement clinker which is coming out from west subdivision of the (i, j) cell (K)
T_N^s = Temperature of cement clinker which is going out from north subdivision of the (i, j) cell (K)
T_S^s = Temperature of cement clinker which is coming out from south subdivision of the (i, j) cell (K)
Δx = Length of subdivision (m)
Δy = Height of subdivision (m)
ρ^a = Density of air (kg/m^3)
u_x^a = Velocity of air in X-direction (m/s)
c_p^a = Specific heat air (kJ/kgK)
u_y^a = Velocity of air in y direction (m/s)
K^a = Thermal conductivity of air (W/mK)
T_P^a = Temperature of air in the (i, j) subdivision (K)
T_S^a = Temperature of air which is coming out from south subdivision of (i , j) subdivision (K)
Re = Reynolds number
u_y^s = Velocity of cement clinker in y direction (m/s)
S_U^s = Source term of cement clinker
T_{in}^s = Inlet temperature of cement clinker (K)
m_0^{aV} = Inlet mass flow rate of air in vertical direction (kg)
$m_{i,m+1}^{aH}$ = Mass flow rate of air in horizontal direction in (i, m+1) subdivision
σ = Stefan-Boltzmann constant (W/m^2 K^4)

$m_{i,m}^{aV}$ = Mass flow rate of air in horizontal direction in (i ,m) subdivision
n = Number of subdivision in x direction
m = Number of subdivision in y direction
ε^{s} = Emissivity of cement clinkers
a_{P}^{a} = Temperature coefficient of air in (i, j) subdivision
a_{E}^{a} = Temperature coefficient of air which is going out from east subdivision of (i , j) subdivision
a_{W}^{a} = Temperature coefficient of air which is coming out from west subdivision of (i , j) subdivision
a_{N}^{a} = Temperature coefficient of air which is going out from north subdivision of (i , j) subdivision
a_{S}^{a} = Temperature coefficient of air which is coming out from east subdivision of (i , j) subdivision
a_{P}^{s} = Temperature coefficient of cement clinker in (i, j) subdivision
a_{E}^{s} = Temperature coefficient of cement clinker which is going out from east subdivision of (i , j) subdivision
a_{W}^{s} = Temperature coefficient of cement clinker which is coming out from west subdivision of (i , j) subdivision
a_{N}^{s} = Temperature coefficient of cement clinker which is going out from north subdivision of (i , j) subdivision
a_{S}^{s} = Temperature coefficient of cement clinker which is coming out from south subdivision of (i , j) subdivision
T_{in}^{a} = Inlet temperature of air
J_H = Chilton-Colburn factor
α_{t} = Under-relaxation factor of temperature
μ^{a} = Viscosity of air
Φ_{s} = Spehericity of cement clinker.
S_{U}^{a} = Source term of air

NOMENCLATURE OF COMPUTER MODEL FOR CLINKERCOOLER

AE	Coefficient of temperature of east side cell
A_FACTOR	Convective area factor between air and clinker particles
ALPHA	Under relaxation coefficient
AN	Coefficient of temperature of north side cell
AS	Coefficient of temperature of south side cell
ATOLD	Temperature of air found in previous iteration
ATSOLD	Temperature of solid found in previous iteration
AW	Coefficient of temperature of west side cell
CP_A	Specific heat capacity of air
CP_S	Specific heat capacity of cement clinker
DEN_A	Density of cooling air
DEN_ACTUAL	Density variation of air with respect to temperature
DEN_S	Density of cement clinker
DIFF_A	Diffusitivity of air
DP_S	Diameter of cement clinker particle
EMISS	Emissivity of clinker particles
HB	Height of bed in clinker cooler
H_CONV	Convective heat transfer coefficient between air and clinker
JO	Chilton-Colburn factor
KA	Thermal conductivity of air
KINVIS_A	Kinematic viscosity of air
KS	Thermal conductivity of cement clinker
LEN_G	Length of clinker cooler
M	Number of subdivision in Y direction (along the bed height)
MA_IN	Inlet mass flow rate of air in clinker cooler
MAFLUX	Mass flux rate of air

MSA_H	Mass flow rate of air in horizontal direction (along the length)
MSA_V	Mass flow rate of air in vertical direction (along the height)
MS_IN	Inlet mass flow rate of hot cement clinker in clinker cooler
N	Number of subdivision in X direction (along the length)
P	Variable for initial guess of solid temperature profile (TS=PX+Q)
POROSITY	Porosity of the bed
PR	Prandtl number
Q	Variable for initial guess of solid temperature profile (TS=PX+Q)
QLOSS	Energy loss in clinker cooler
RE	Reynolds number
SP	Source term
STEP_CONST	Stefan-Boltzmann constant
TA	Cooling air temperature in any subdivision
TA_IN	Inlet temperature of cooling air in cooler
TDM_A	Solving parameter for TDMA technique
TDM_C	Solving parameter for TDMA technique
TS	Cement clinker temperature in any subdivision
TS_IN	Inlet temperature of hot cement clinker in cooler
VA_IN	Inlet velocity of air in clinker cooler
VIS_A	Viscosity of air
VGRATE	Grate speed
WIDTH_G	Width of grate