International Journal of Scientific Engineering and Technology (ISSN : 2277-1581)
Volume No.2, Issue No.7, pp : 631-637 1 July 2013

Mass and Energy Balance in Grate Cooler of Cement Plant

Raziuddin Ahmad[1], Tasmeem Ahmad Khan[2], Vedika Agarwal[3]

.[1,2] Department of Mechanical Engineering, Al-Falah School of Engineering and Technology, Faridabad, Haryana, India

[3] Manager / System Technologies, STEAG Energy Services (India) Pvt Ltd**.,** Sector – 16, Noida U.P., India

Email : raziuddina@gmail.com

Abstract—O*bjective of this paper is development of first principle based model of grate cooler for cement plant. In this work, the temperature variation and assumptions of the model will be discussed. The model is developed for steady state condition. Variations of gas, solid temperature, wall temperature and heat losses through the wall are simulated with respect to grate cooler length. The model is validated by comparing the output with the published experimental simulation data and by observing the response to step changes. Step changes are used for validation and to understand the influence of various design and operating parameters on grate cooler performance*.

I. INTRODUCTION

The process of cement manufacturing in simple terms can be described as grinding limestone in a suitable manner so as to convert them into clinker and then further grinding it at a suitable temperature to finally yield cement. There are two processes known as Wet and Dry processes which are usually employed in cement manufacturing. The grinding and mixing operation takes place in the both wet and dry conditions.

A grate cooler can be regarded as a simple heat exchanger through which the clinker passes across or counter to the cooling air flow and a direct heat transfer takes place between the hot clinker and the cold cooling air. The desired maximum recuperation of the heat from the clinker cooler for use in the kiln system for specific quantities of secondary and tertiary air demands that these combustion air quantities drawn from the cooler have the highest possible temperature. To obtain maximum possible clinker cooling using the lowest possible cooling air volumes, it is necessary for the clinker to remain in the cooler for a particular length of time and for the cooler to achieve the best possible distribution of clinker and cooling air. The hot clinker from kiln are discharged in the grate cooler at temperature of 1250°C–1400°C.As the clinker moves with uniform speed along the cooler length, solid lose its heat to cross flow air. The air moves below the clinker bed to upward from the fan. A part of air is generally sent to the kiln as secondary air, a part to calciner as tertiary air and a part is vented to the surroundings. The air depressions created at the entry and the exit of the exchanger divide the cooler, whose walls coating is made with refractory bricks, into two zones, named hot and cold zones. The clinker goes to silos at a temperature of 100°C (approx). The main objective of grate cooler is recovery of heat from clinker by air which is then used for combustion of fuel.

In this work, mass energy balance equation is developed for grate cooler. Using this we obtained output temperature of clinker from cooler, wall temperature of grate cooler and heat loses through the wall. Several numerical simulations were carried to understand the influence of operational parameters like clinker inlet temperature or its combustion, airflow rate on the performance of grate cooler.

The proposed model along with preheater & kiln model will helpful in developing of simulator for cement plant. This model will also be helpful for choosing operational parameter.

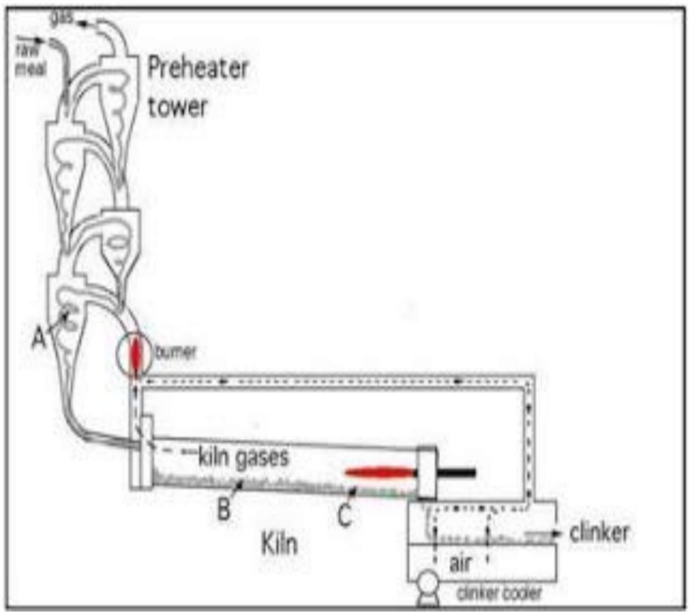

Fig.1. cement manufacturing process

II. MATERIALS AND METHODOLOGY

A. Modelling of Grate cooler

For modelling of grate cooler following assumption are made.

-The heat capacity of air is assumed a constant throughout the grate cooler.

-Solid (Clinker) is of uniform particle size and constant porosity.

-Air enters in a cross flow mode with respect to solid.

-The distribution of air in the bed is uniform.

-Conductive heat transfer will occur in both horizontal and vertical direction.

-Heat capacity of clinker input and output at each section is same.

-The fine particle transported by air flows and crossing the grate slits is negligible.

-The porosity of the clinker bed is equal to 0.4.

-The clinker bed is uniform and rectangular in both hot and cold zone.

-The flow of air through the bed is defined by superficial velocity.

-The clinker and air output temperature of each section from grate cooler is equal.

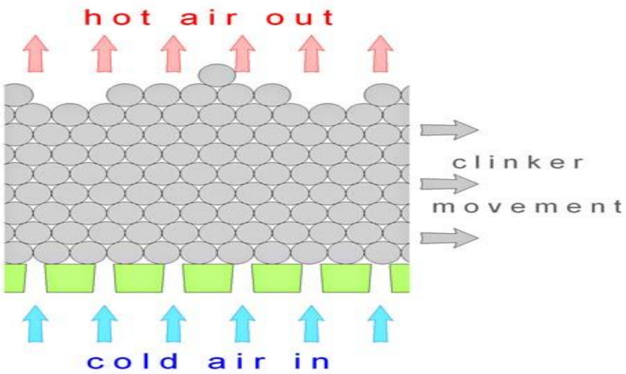

Figure 2-Model of grate cooler

For modeling of grate cooler, grate cooler is divided into two zones warm and cold. Clinker bed in grate cooler assumes which is rectangular. The whole clinker bed is divided into number of stages and number of stages depends upon the height, length mass, density, width, residence time of clinker. For modeling of grate cooler first, mass and energy balance in grate cooler is performed.

B. Mass Balance in Grate Cooler:-

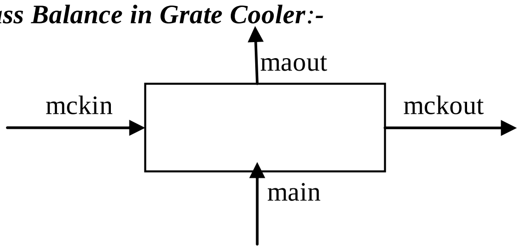

Figure 3-Mass balance in grate cooler

The mass flow rate of clinker input and output is same because mass flow rate in grate cooler remain constant.

mckin + main – maout – mckout = 0

C. Energy Balance in the Grate Cooler

The main function of cooler is to cool the clinker and transfer the energy to air. The clinkers are losing heat by conduction and convection to the cooling air coming from fan below the clinker bed. This air is then use as a secondary or tertiary in kiln & preheater respectively. The cooler is in continuous mode and we are assuming it to be steady. So there will be no accumulation of energy in any stage. Energy balance is applied in each stage of grate cooler. By energy balance, we can find temperature of clinker and air at various stages. Last stage gives the outlet temperature of grate cooler. Consider any ith section and energy balance for that section can be represented as:-

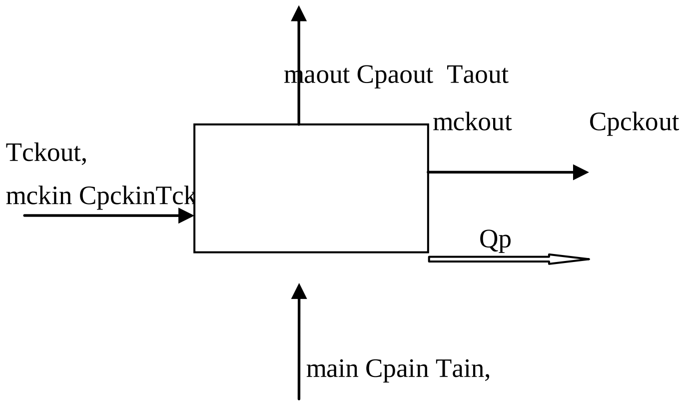

Figure 4-Energy balance in "ith" section

The general energy balance equation is given by

mckin*hckin + mairin*hairin = mckout*hckout + maout*hairout + Qp

The energy balance equation for ith section is given by:-

$$(mckin_i Cpckin_i Tckin_i) + (main_i Cpain_i T_o) = (mckout_i Cpckout_i Tckout_i) + (maout_i Cpaout_i Taout_i) + Qp_i \quad (i)$$

The specific heat capacity of clinker at any section is obtained with the help of output temperature of clinker of just before section.

$$Cp_i = a_i T^0 + b_i T + C_i T^2 + d_i T^3$$

Where a, b, c and, d are clinker heat capacity expansion coefficient.

Table 1 Clinker coefficient

a	0.1742
b	1.41e-4
c	1.28e-7
d	5.07e-11

Specific heat of air can be obtained in a manner similar to clinker.

Now, number of stages in warm zone and cold zone are calculated. If we assume total number of stages is "N" and number of stages in warm zone as "K" then number of stages in cold zone are (N-K) "L". The number of stages depends upon residence time.

$$K=\frac{Hc\ \ Lc\ \ w\ \ Dck}{mck\ \ tr},\qquad L=\frac{Hf\ \ Lf\ \ w\ \ Dck}{mck\ \ tr}$$

Height of clinker bed in warm and cold zone depends on the frequency of grate, mass flow rate of clinkers, width of clinker bed. Height of clinker bed in warm and cold zone is given by;

$$Hc=\frac{mckin}{C\ \ Wc\ \ Dck\ \ w}\qquad Hf=\frac{mckin}{C\ \ Wc\ \ Dck\ \ w}$$

The heat transfer take place in each section through conduction or convection and due to this clinker comes out from the cooler at 100 degree C (approx).The heat losses in each section depends upon heat transfer coefficient, thermal resistance and heat transfer area. Now heat losses and thermal resistance in each section is given by;

$$Qp_i=\frac{1}{Rt_i}\ (Tp_i - T_0\ ),\qquad \text{(ii)}$$

$$Qp_i\ = hf_i\ A_i\ (T_i - Tp_i\ ),\qquad \text{(iii)}$$

The thermal resistance of any section depends upon area, thickness of bricks, thermal conductivity of bricks, thickness of shell, thermal conductivity of shell, & convection heat transfer coefficient.

$$Rt_i=\frac{1}{A_i}\left(\frac{tbr}{tcbr}+\frac{ts}{tcs}+\frac{1}{hc}\right)\qquad \text{(iv)}$$

D. Model for Calculating Convective Heat Transfer Coefficient between Clinker and Air;

The dominating mode of heat transfer in the cooler is convection between the clinker particles and the flowing air. The convection heat transfer coefficient (hc) can be calculated from the following expression.

$$hc=\frac{Nu\ Ka}{Ds},\qquad Nu = 0.0295\ .\ Re^{\frac{4}{5}}.\ \ Pr^{1/3}$$

The Reynolds and Prandtl numbers are given by the following equation.

$$Pr=\frac{Da\ Cpair}{Ka},\qquad Re=\frac{Ds\ Da\ \ Ua}{(1-poro\ ).\ sphers\ Dvis_{air}}$$

The thermal conductivity and viscosity of air are calculated at the average temperature of clinker and air (T s + Tg) / 2. The heat capacity of air for each section assumes input and out is constant.

Table 2.Grate cooler input parameter

Description	Units	Air	Clinker
Thermal conductivity	J/m.s.k	(7e-5.T +0.0042)	0.5
Viscosity	kg/m.s	(1.511e-6.T^1.5)/(T+120)	
Emissivity	unitless		0.78
Porosity	unitless		0.4
Density	kg/m3	1.184	1500
Heat Capacity	J/kg.K	1009	1000
Particle Diameter	m		0.007
Particle sphericity	unitless		1
Input Temperature	K	304	1673

E. Derivation for Calculating Output Parameter of Grate Cooler:

By solving equation (i), (ii), (iii) and (iv), we find various output variables of grate cooler. The detailed model equations of grate cooler are given in Table 3.

Table 3 Equation system for the grate cooler sub model (i=1, 2, 3 ...)

Temperature of each section	$T_i=\frac{((mck_iCpck_iTckin_i\ + ma_iCpa_iT_O\ )\ (1+Rt\ hf\ \ A))\ +(hf\ \ A\ To)}{((mck_iCpck_i+ma_i\ Cpa_i\ )\ \ (1+Rt\ hf\ \ A))\ +(hf\ \ A)}$
Specific heat capacity of clinker and air in each section	$Cpck_i\ = a_i(T_i)^0+\ b_i(T_i)\ +\ c_i(T_i)^2+d_i(T_i)^3$
Wall temperature of each section	Tp_i = ((Rt hf A T_i) + To) / (1 + Rt hf A))
Heat loses form each section	Qp_i= hf A $(T_i\ - Tp_i)$

III. RESULTS VALIDATION AND DISCUSSIONS

The process model is implemented and simulated in MATLAB. The validation data is obtained from the cement plant. Given the grate cooler system in the steady state operation, some step changes are preformed on input variables in order to investigate the dynamic behaviour. The open loop process responses for the key output variables are evaluated. Inputs considered are as follows:-

Table 4.Grate cooler input parameter

Mass flow rate of clinker	kg/s	49.13
Mass flow rate of air	kg/s	135.6
Length of clinker bed	meter	30
Width of clinker bed	meter	4
Clinker temperature	Kelvin	1673

A. Model is executed with these inputs. The results are as follows:-

*1. **Analysis of clinker and air temperature***

From figure-5 we can see clinker or air temperature gradually decreases with respect to length of grate cooler and it is clear that clinkers temperature decreases only due to conduction and convection from clinker. The clinker and air temperature are decreases due to fact that heat energy decreases in clinker along the length.

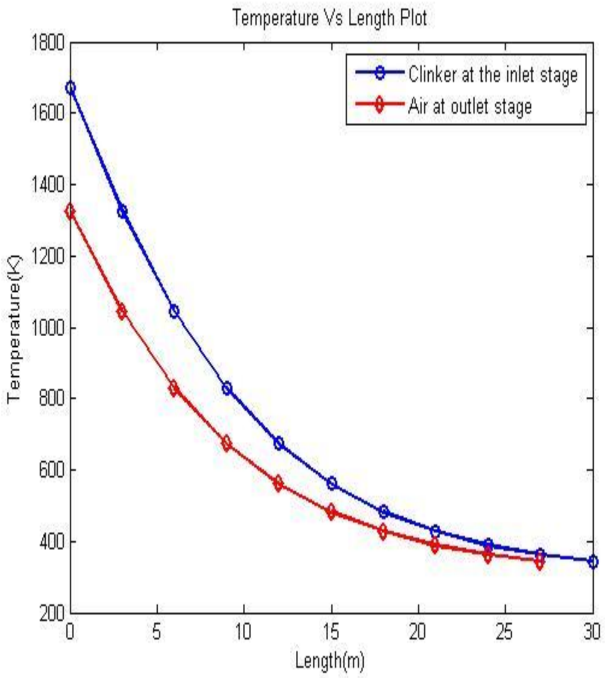

Figure-5 clinker and air temperature along the length

2 Analysis of wall temperature

From figure-6 we can see wall temperature gradually decreases with respect to length of grate cooler and it is clear that wall temperature decreases only if conduction from clinker decreases. The conduction from clinker is decreases due to the fact that heat energy decreases in clinker along the length. The wall temperature decreases more quickly in warm zone's compared to cold zone. This is due to thermal losses by radiation.

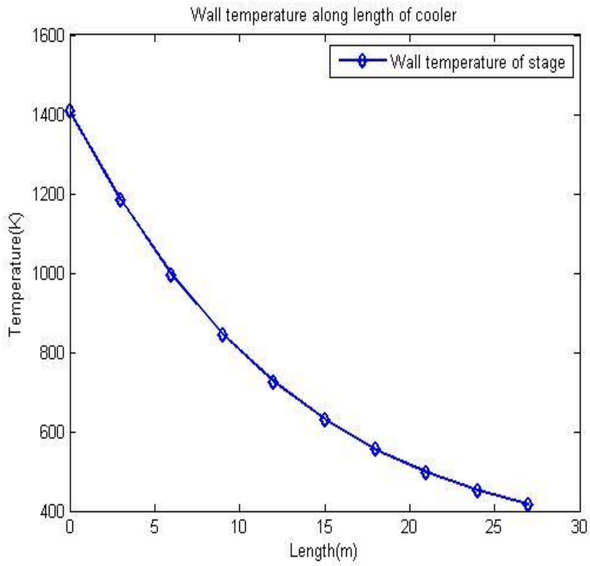

Figure-6 Wall temperature along length of grate cooler

3. Analysis of Heat Losses

In this case, we can see from Figure-7, that heat losses decreases with respect to length or sections because heat energy is continuously decreasing due to convection by cross flow air or conduction through the surface of grate cooler. So heat energy at the cooler exhaust is minimums in comparison to heat input through clinker.

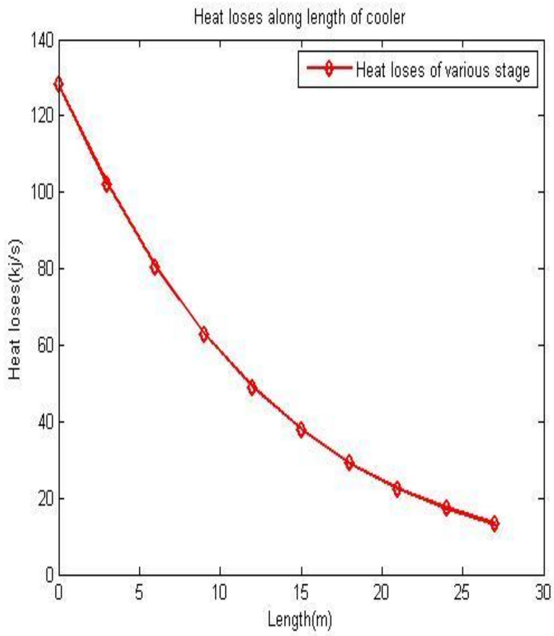

Figure -7, Heat losses in grate cooler

International Journal of Scientific Engineering and Technology (ISSN : 2277-1581)
Volume No.2, Issue No.7, pp : 631-637 1 July 2013

B. Step responses are performed and results are analysed same as before:-

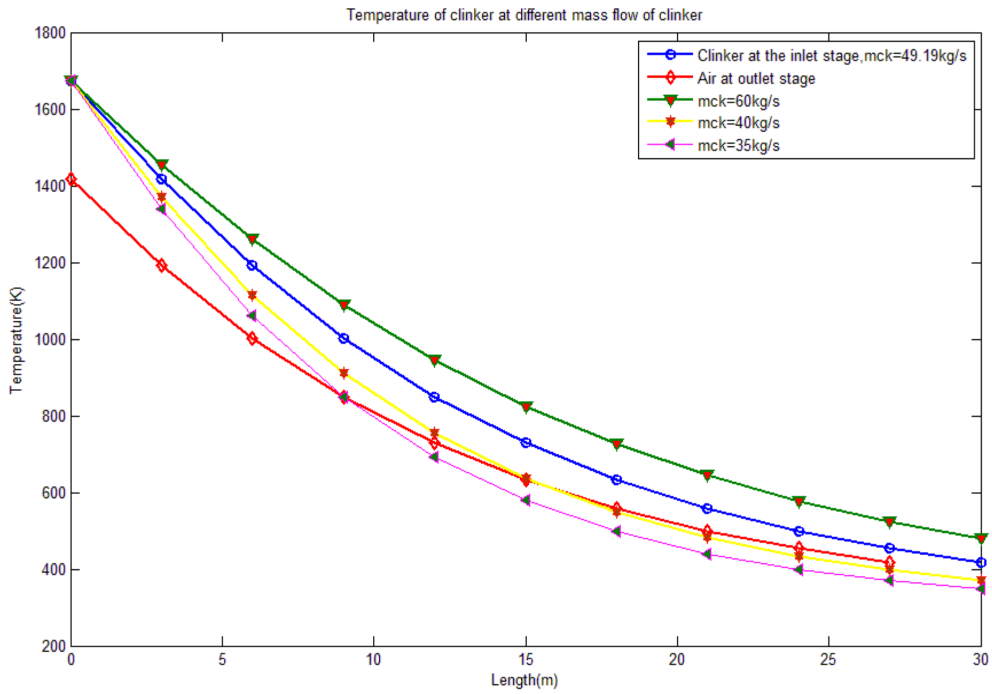

Figure 8-At different mass flow of clinker it effect on temperature of clinker

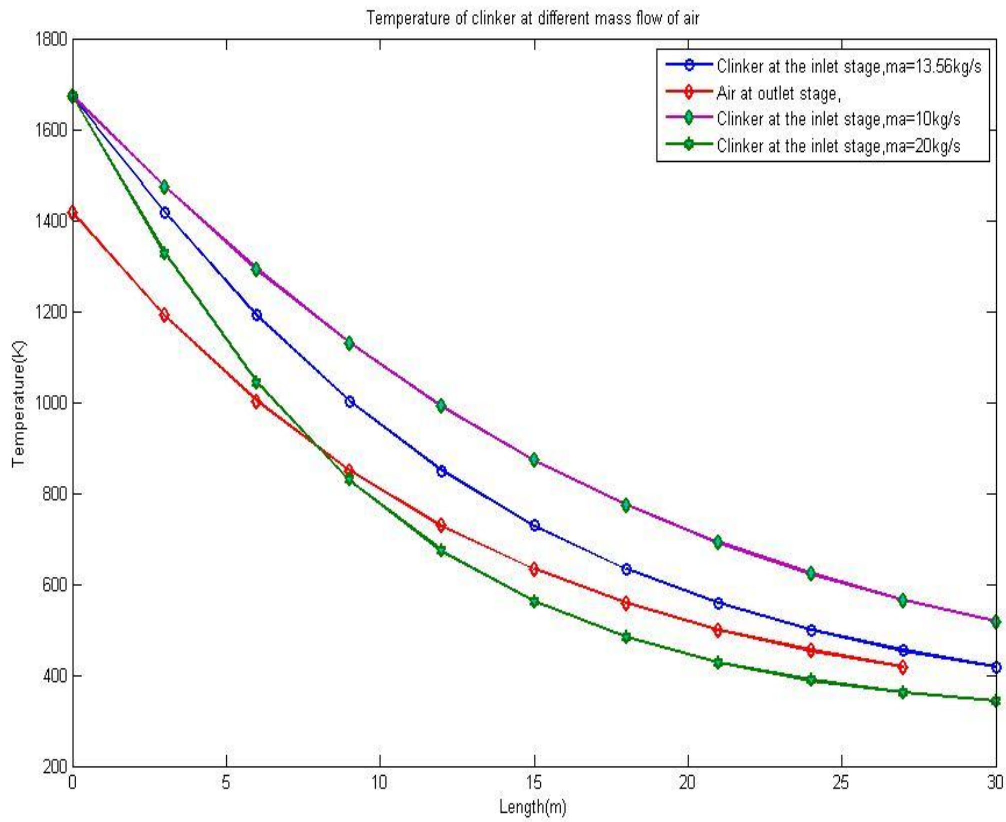

Figure 9 – At different mass flow rate of air, effect on temperature of clinker

*1. **Change in mass flow rate of clinker***

In this case we take all input data of grate cooler to be same except mass flow rate of clinker. We take different mass flow rates of clinker input to grate cooler and analyses its effect on temperature of output clinker of grate cooler. For validation of model, we take different mass flow like 60kg/s, 49.13kg/s, 40 kg/s and 35 kg/s.

From figure-8, we can see that the increase mass flow rate of clinker with increase temperature and decrease mass flow rate of clinker with decrease temperature of clinker. This is because we increase and decrease clinker mass flow rate but all other to be maintain constant. Due to this heat input in grate cooler increases or decrease according to mass flow rate of clinker but heat transfer between clinker and air is same. It is clear from the result that the mass flow rate of input clinker is directly proportional to temperature of clinker. The main objective of grate cooler is to cool the clinker at minimum temperature and maximum recuperation heat. Therefore we can find optimum mass flow rate of clinker for recuperating maximum heat.

2. Change in mass flow rate of air

In this case we take all input data of grate cooler to be same except mass flow rate of air. We take different mass flow rates of air input to grate cooler and analysis its effect on output temperature of clinker of grate cooler. For validation of model, we take different mass flow of air like 10kg/s, 13.56kg/s and 20 kg/s.

From figure-9, we can see that the increase mass flow rates of air with decrease temperature of clinker and decrease mass flow rate of air with increase temperature of clinker. This is because we increase and decrease only mass flow rate of input air and maintain other inputs of model as constant. Due to this heat transfer between air and clinker increases or decreases according to mass flow rates of air. This result shows, the mass flow rate of input air is inversely proportional to temperature of clinker. It is clear from the above result that the recuperation of heat energy is maximum when mass flow of air increases. So we need to find out the optimum mass flow rate of air for which recuperation energy is maximum and the mass flow rate of air and its temperature is suitable for coal burning in rotary kiln and calciner.

IV. CONCLUSIONS

A steady state model for the cement grate cooler system has been developed and presented. The model is based on simple equation of mass & energy balance. The static solutions of the model are validated using experimental data and accuracy is satisfactory. The response is follows the operational rules. This model shows that change in mass flow rate of clinker and air can control clinker output temperature or secondary air temperature. Therefore it can be used for finding optimum mass flow rate of clinker or air for recuperating maximum heat and also for optimization of grate cooler thermal efficiency.

The model has not yet been validated on the real time data, and the results of dynamic response are only qualitative. The further work has to be done to obtain the quantitative results of dynamic response.

ACKNOWLEDGMENT

The authors thank STEAG Energy Services (India) Pvt Ltd., for providing the necessary facilities and financial support to undertake the above work. I express my deepest gratitude to Mr. Prabir Purkayastha, Head of Department System Technologies for providing me the opportunity for doing internship at such a distinguished company.

REFERENCES

i. Mujumdar, K., Ganesh, K., Kulkarni, S., and Ranade, V., Rotary cement kiln simulator (RoCKS): Integrated modeling of pre-heater, calciner, kiln and clinker cooler. Chemical Engineering Science, 62(9), 2590–2607. 2007,

ii. Oscar Acu˜na _ Carla Martin-Villalba __ Alfonso Urquia, Virtual-Lab of a Cement Clinker Cooler for Operator Training URL- http://www.ifac-apersonline.net/Detailed/58631.html

iii. H.P.Elkajaer, T.Enkegaard, "Operation of Grate Cooler and a method of evaluating their efficiency", Zement Kalk Gips, Jahrgang, pp. 510-518, 10/1992

iv. I. Barin, O. Knacke O. Kubachewsky *Thermochem -ical Properties of Inorganic Substances*, Springer Verlag, Berlin, 1977.

v. D. Touil , H. F Belabed , C. Frances, S. Belaadi " Heat Exchange Modeling of a Grate Clinker Cooler and Entropy Production Analysis", Paper published in International Journal of Heat and Technology Vol. 23, pp 61-68, 2005.

vi. D. Touil, Les bilans d'énergie et d'exergie dansl' industrie de ciment, *Ciments, Bétons, Plâtres, Chaux*, Vol. 4/815, pp. 250-253, 1995

vii. C. Perry, *Chemical Engineering Handbook*, fourth edition, MacGraw Hill, New York, 1980.

viii. Figure-2, http://www.cementkilns.co.uk/cooler_grate.html

ix. Figure-1, http://constructionduniya.blogspot.in/2012/02/cement.html

X. Input data of grate cooler.

G o o g l e automatically generates this HTML view of the file http ://cdm.unfccc.int/UserManagement /File Storage/R7Q7TOUDYP_FEJZC4QO00J9B33E7VVI as we crawl the web.

NOMENCLATURE

a	air	
A1	Average heat transfer area	m2
c	Warm zone	
ck	Clinker	
Cp	Specific heat capacity	kj/kgK
C	Distance covered by grate	m
Ds	Clinker particle diameter	m
D	Density	kg/m3
$Dvis_{air}$	Dynamic viscosity of air	kg/m.s
f	Cold Zone	
g	gas	
H	Height	m
hc	Convective heat transfer coefficient	W/m2K
hf	Average heat transfer coefficient	W/m2K
h	Specific enthalpy	kj/kg
in	input	
j	Section	
k	Number offstage in warm zone	
Ka	Thermal conductivity of air	kj/m.s. K
L	Number offstage in warm zone	
Lc	Length of clinker bed in warm zone	m
Lf	Length of clinker bed in cold zone	m
m	Mass flow rate	kg/s
out	output	
o	Dead zone	
Nu	Nusselt number	
P	Prandt number	
poro	Porosity	
Qp	Flow of heat dissipation losses	KW
Re	Reynolds number	
Rt	Thermal resistance	[Wm-2K-1]-1
sphers	Sphericity of clinker particle	
T	Temperature	K
Tp	Wall Temperature	K
tr	Average residence Time	s
tbr	Thickness of bricks	m
tcbr	Thermal conductivity of	Wm-1K-1
ts	Thickness of shell	m
tcs	Thermal conductivity of bricks	Wm-1K-1
Uo	Velocity of air	m/s
Wc	Frequency of grate in warm zone	s-1
Wf	Frequency of grate in cold zone	s-1
w	Width	