IMPROVED WASTE HEAT RECOVERY THROUGH SURFACE OF KILN USING PHASE CHANGE MATERIAL

by

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The heat losses that occur from the surface of the rotary kilns during calcination process are a major source of waste heat in cement production industry. In order to recover this heat, a multi-shell heat exchanger that forms an annular duct over the high temperature zone of the kiln is used. The phase change material (PCM) paraffin wax with a melting point of 68 °C is filled in between the gap of the two concentric annular steel shells which are thermally insulated from the outside. In order to draw a comparison and to establish that phase change material improves the waste heat recovery, the heat exchanger model made up of mild steel, which extracts waste heat from a kiln, is experimentally investigated with and without the tertiary shell that contains the phase change material. The outer surface of the heat exchanger is insulated by glass wool, and to facilitate the passage of air between the shells for heat transfer, a variable speed centrifugal fan (for variable flow rate) is installed. The results show that the waste heat recovery rate is increased by 3% to 8% (depending on different air-flow rate) with the use of phase change material. This implies that phase change materials such as paraffin wax can be used in heat exchangers to obtain an improved waste heat recovery rate.

Key words: *heat exchanger, phase change material, waste heat recovery, rotary kiln, paraffin wax*

Introduction

The rotary kilns are used all over the world by different industries to produce variety of products like cement, lime, alumina, vermiculite, magnesia, and iron ore pellets. They are also used for roasting a wide variety of sulfide ores prior to metal extraction. Cement production is one of the most energy demanding industrial processes. Thus, the amount of heat wasted in the process is high ranging from 8-15% of the total heat input [1]. There are various works available on waste heat recovery in the cement sector which includes waste heat recovery from flue gases and recovering waste heat from the surface of rotary kilns. While the former has attracted much of the attention of the industries and waste heat recovery plants for flue gases are installed by cement production units all over the world [2], the latter remained unpopular due to some practical and technical issues regarding function of the kiln. The kiln in a cement

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plant rejects considerable amount of heat to the atmosphere through its surface. So, by suitably designing and installing the waste heat recovery system over the kiln shell, heat can be extracted. Recently, a model of rotary kiln used for calcination of dolomite in magnesium production in which a heat exchanger is proposed by Karamarković *et al.* [3]. It uses both convective and radiant heat loss from the surface of kiln shell and prevents overheating, does not require air tightness and is implementable over rotary kilns with analogous surface temperature distribution. In this paper, the concept used for experimental model proposed and designed for cement production process is somehow similar to the system proposed for magnesium production. However, our model employed different geometrical, thermal and air-flow conditions necessary for cement production. Moreover, as this paper aims to establish the improvement in waste heat recovering capacity of the system, we have used paraffin wax 6499 as the phase change material in our experimental model and a comparison is made in order to establish that PCM improves the waste heat recovery. Thus, the concept of thermal energy storage (TES) [4] is used as there is a time difference between the energy consumption and energy generation.

The PCM are generally used for the purpose of TES by making use of latent heat of a PCM, for storing heat with large energy densities in combination with rather small temperature changes and also to stabilize the temperature [5]. Latent heat storage is one of the most efficient ways of storing thermal energy [6]. As in this model, the surface of the kiln releases a sufficient amount of energy through convection and radiation. The PCM absorbs this heat and releases it when the working fluid comes in contact with it. The stored energy during a latent storage process can be evaluated as: $Q = mL$ where m denotes the mass and L is the specific latent heat of the PCM [7]. Generally PCM are classified into two types: Organic PCM *e. g.* paraffin wax and inorganic PCM *e. g.* salt hydrates [8]. We have used paraffin wax which is an organic PCM in our model, based on the consideration that suitable PCM should possess desirable thermophysical, kinetics and chemical properties as described in [9, 10]. Paraffin wax used in our model contains a mixture of mostly straight chain n-alkanes CH_3–(CH_2)–CH_3. The crystallization of the (CH_3)-chain discharges a great amount of latent heat. Both the melting point and latent heat of fusion increase with chain length. The paraffin is suitable as heat of fusion storage materials due to their large temperature range availability. As we have to consider the economic factors involved in these systems, the technical grade paraffins are used as PCM in latent heat storage systems. One of the reasons that we have used paraffin is because it is safe, reliable, predictable, less costly and non-corrosive and their properties like chemical inertness and stability below 500 ºC. They also show small volume changes on melting and have low vapor pressure in the melt form. For these properties of the paraffins, it can be concluded that a system using paraffins usually have very long freeze-melt cycle [10]. The incorporation of paraffin in our model derives its effectiveness from its property of its excellent stability concerning the thermal cycling, *i. e.* a very high number of phase changes can be performed without a change of the material's characteristics [5]. After making the choice of PCM to be used in the system, the question arises now that how this PCM can be integrated into the system so it may function properly as desired in this system. There are different ways to integrate and use PCM in heat exchanging systems. Encapsulation as discussed by [10] is one of the ways to effectively use PCM. It is then divided into micro- and macro-encapsulation. Micro-encapsulation involves introduction of micro-particles to enhance the heat storage capacity of PCM. This paper does not discuss this method. The paper makes use of the other technique that is macro-encapsulation which involves containment of PCM in some cylinder or shaped body so as it is not affected by the surrounding environmental impurities. Though it has certain disadvantages too, however they are suitable for industrial usage and higher temperatures. So, in our case we enclosed the PCM in between the second and the tertiary shell and suitable measures were taken so as to prevent PCM from leaking out of the enclosure. The idea to use PCM in waste heat recovery is relatively a new one and recently used to recover heat from Diesel engine exhaust [11]. Other interesting applications where heat transfer efficiency improvement is important are given in [12-16].

Therefore, the model presented in this paper considers a heat exchanger, consisting of two concentric annular thermally insulated shells which surround the rotary kiln and carries paraffin wax as a PCM. The model determines convective and radiant heat losses in order to find out total heat loss of the bare kiln. It also evaluates the amount of recoverable waste heat from the surface of the kiln shell for a designated mass-flow rate of the working fluid which is air in this case, and thermal conductivity, respectively. The paper discusses the design, fabrication and experimental investigation of a prototype rotary kiln, along with the heat exchanger. This set-up contains thermally insulated suction pipes as well which are connected to the outermost shell and their other ends are connected to the input of variable speed centrifugal fan in order to achieve different flow rates. To further increase the efficiency of the waste heat recovery system, we have installed glass wool as insulating material for secondary shell, as it has lower thermal conductivity as compared to mineral wool resulting in increased overall system efficiency. The prototype is so designed that it also allows changing the main geometrical parameters of the system in order to investigate the performances of different configurations of the heat exchanger thus it enables us to establish a comparison between results with and without using PCM. This paper is committed to the improvement of waste heat recovery through surface of a rotary kiln by the use of paraffin wax as a PCM inside a heat exchanger installed above the kiln that efficiently extracts the maximum heat loss: radiant and convective.

Governing equations

The total heat loss from the surface of bare kiln is the sum of convection and radiation heat transfer *i. e.* $Q_{\text{kiln}} = Q_{\text{conv.}} + Q_{\text{rad.}}$

$$Q_{\text{kiln}} = hA_k \Delta T + \left[\varepsilon \sigma A_k T_1^4 - T_2^4 \right] \tag{1}$$

where h, A_{k}, ΔT, ε, and σ are convective heat transfer coefficient, area of the kiln, temperature difference, emissivity of the surface, and the Stefan-Boltzmann constant, respectively.

Following are the formulas required to solve eq. (1):

$$A_k = 2\pi rl \tag{2}$$

where r and l are radius and length of the kiln shell, respectively:

$$h = \frac{\text{Nu}\, k}{L} \tag{3}$$

where Nu and k are Nusselt number and thermal conductivity, respectively, and L being the characteristic length which is equal to the outer diameter of the kiln.

The relationship that applies to the average dimensionless heat transfer coefficient for free convection around a horizontal cylinder [17]:

$$\text{Nu} = \left\{ 0.60 + 0.387 \left[\text{Ra}\, f_3(\text{Pr}) \right]^{1/6} \right\}^2 \tag{4}$$

The characteristic length, L, from which the Nusselt and Rayleigh numbers are calculated:

$$L = D \tag{5}$$

The function $f_3(\text{Pr})$ describes the effect of the Prandtl number over the entire range $0 < \text{Pr} < \infty$ and is given:

$$f_3\left(\text{Pr}\right) = \left[1 + \left(\frac{0.559}{\text{Pr}}\right)^{\frac{9}{16}}\right]^{-\frac{16}{9}} \tag{6}$$

Rayleigh number can be computed by the relation presented in [18]:

$$\text{Ra} = gl^3\beta\frac{T_\text{s} - T_\text{a}}{k\nu} \tag{7}$$

By finding out total heat loss from bare kiln surface a comparison has been made for heat extracted through application of secondary shell and total heat loss of the kiln. This comparison enabled analysis of efficiency for proposed model with and without PCM.

Following equation is used to find out total heat extracted:

$$Q_{out} = \dot{m}C_p\Delta T \tag{8}$$

where C_p and $\dot{m}$ are specific heat at constant pressure and mass-flow rate, respectively.

$$\dot{m} = \rho VA \tag{9}$$

where ρ is the density of the air, V – the velocity, and A – the area of the fan outlet.

Calculations

Equation (2) has been solved for area of kiln using dimensions provided in tab. 1 which is equal to 0.4864 m^2. To solve eq. (3), eqs. (4)-(7) are solved. All the values for dry air have been obtained at the working fluid ambient temperature from the properties tables presented in [19-21]. These obtained values are shown in tab. 2.

Nusselt number in eq. (4) thus calculated has value 78.53. The characteristic length used is the diameter of kiln shell eq. (5) for the calculation of convective heat transfer coefficient in eq. (3). The calculated value for convective heat transfer coefficient at a surface temperature of 231.2 °C is 8.2 W/m^{2}K which is in range as per calculation carried out at similar surface temperature of 241 °C presented in [3] having the value of 8.19 W/m^{2}K. The length of section for which the values are compared is 1 m being close to length of kiln shell being considered in this paper. Now that all the required parameters are established for calculation of eq. (1), the heat loss from the surface of bare kiln is thus determined. This heat loss is compared to the total heat input to find out percentage heat loss of the input through kiln surface.

Table 1. Dimensions of the experimental set-up

Parameter	Value [m]
Length of kiln shell	0.609
Diameter of kiln shell	0.254
Length of secondary shell	0.550
Diameter of secondary shell	0.267
Length of tertiary shell	0.550
Diameter of tertiary shell	0.280

In order to find out extracted heat, the mass-flow rate and the temperature difference are calculated. The value for specific heat at constant pressure *i. e.* 1.005 kJ/kgK is obtained from [19] at given ambient temperature. Mass-flow rate is calculated using the relation shown in eq. (9). The obtained value for density of dry air at ambient temperature is 1.13 kg/m^3 and heat extracted at different flow rates is thus calculated at fan outlet area of 0.00316 m^2.

Heat loss because of convection from the surface of kiln:

$Q_{conv.} = 806.47$ W

Heat loss because of radiation from the surface of kiln:

$Q_{rad.} = 1087.04$ W

Total heat loss of the bare kiln:

$Q_{total} = 1893.51$ W

The heat loss thus obtained is 94.67 % of the total heat input to the system *i. e.* 2000 W.

Table 2. Parameters for calculation

Parameter	Value	Unit
Rayleigh number	$2.913 \cdot 10^8$	–
Constant of thermal expansion	$3.3184 \cdot 10^{-3}$	K^{-1}
Kinematic viscosity	$161.8 \cdot 10^{-7}$	m^2/s
Thermal diffusivity	$228.7 \cdot 10^{-7}$	m^2/s
Prandtl number	0.70	–
Nusselt number	78.538	–
Characteristic length	0.254	m
Convective heat transfer coefficient	8.2	W/m^2K
Surface temperature	231.2	°C
Ambient Temperature	29	°C

Experimental investigation

Experimental Set-up

A prototype rotary kiln was designed and tested. Mild steel sheets having gauge 18 thickness were used in the fabrication of steel shells. The core component in the experimental set-up was the heating source. The heating requirements of the set-up were fulfilled by electric heating rods. Two rods having a power of 1000 W each providing total heat input to the system of 2 kW were suspended inside the kiln shell along the central horizontal axis. To hold the rods inside the hollow, kiln shell steel fixtures of minute thickness and width were used. To prevent the inner shell from conducting electricity, ceramic holders were used to hold the rods.

The inner shell was riveted by forming a lap joint. The length of the kiln shell was 0.6096 m, and its diameter is 0.254 m. The shell was sealed from both the ends and inside the shell was the heating source.

A secondary shell (also made up of mild steel) having larger diameter than inner shell was used to cover it. This shell was different than inner shell in terms of dimensions and provision of holes for air delivery as shown in figs. 1-3. The air suction holes were formed on the outer shell over the section of the kiln where temperature was higher than other sections of the kiln. The shell had a length of 0.558 m and diameter of 0.2677 m. There was thus an intentionally provided gap between inner and outer shell to allow flow of ambient air.

To fill the paraffin wax PCM, a third shell was manufactured having greater diameter than the secondary shell. Paraffin wax was filled in between second and third shell by melting it. Both ends were properly sealed to ensure proper encapsulation of PCM. In order to insulate the outermost shell glass wool insulation was used. This allowed prevention of radiation heat loss from outer shell's surface.

The whole assembly was placed over a wooden stand, care was taken to ensure proper designing of the stand to ensure equidistant gap between inner and outer shells.

A variable speed centrifugal fan was used, connected to the apparatus via insulated flexible pipes. Each pipe had 1.8 m length, with one end connected to the fan inlet and the other end connected to the secondary shell's air outlet.

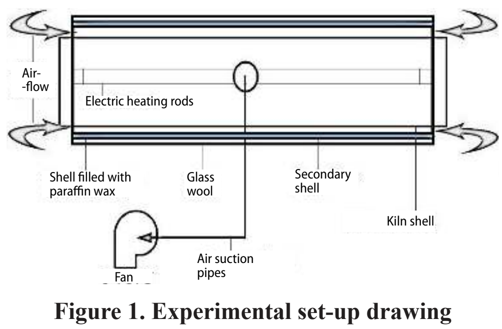

Figure 1. Experimental set-up drawing

Experimental procedure

The experimental procedure was divided into three major steps. First step was to monitor

Figure 2. Experimental assembly

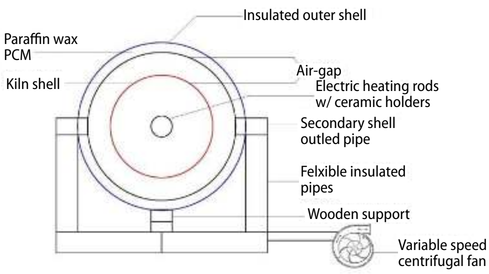

Figure 3. Experimental set-up cross-sectional view

thermal distribution of bare kiln shell. Second step was to calculate heat extraction from kiln using a secondary insulated shell. Third step consisted of welding and sealing a tertiary shell around the secondary shell thus creating a cavity in which PCM was to be poured, both ends were sealed after pouring paraffin wax and outer most shell was wrapped in glass wool insulation. Heat extraction was again calculated and results obtained from step two were compared.

As described in the first step power was provided to the electric heating rods. Kiln shell was continuously monitored for rise in temperature from the start till the steady-state conditions were achieved. It was observed that after 50 minutes of operation there was no more rise in temperature for the kiln shell. The peak temperature recorded was 254 °C and average surface temperature was found out to be at 232 °C.

The second step in the procedure was covering the kiln shell, as it was the main purpose of the experimentation. Therefore, the shell was covered by a secondary shell having larger diameter, hence creating an air-gap between the two shells. This secondary shell was insulated using glass wool insulation and at this stage PCM was not used. Kiln surface temperature was monitored periodically. To prevent heat transfer via conduction it was ensured that no part of the inner shell comes in contact with the outer shell.

Blower was switched on using ambient air as the working fluid, it created suction between the two shells. Air swept over the outer surface of the inner shell, as well as the inner surface of the outer shell simultaneously and carried along the entrapped heat via forced convection to the outlet of the centrifugal fan. With the help of anemometer fan's air velocity was found out and with the help of temperature sensors fan's outlet air temperature was monitored.

Surface temperatures of the kiln, ambient temperature, and the fan's outlet temperatures at different speeds of the fan were noted down. The temperature of glass wool insulation was measured as well, along with the inner wall temperature of the secondary shell. All these readings were used for calculations using the mathematical model. These results were obtained with two shells assembly without utilizing PCM.

In the third step experimentation was carried out with third shell assembled around the secondary shell. Procedure for this step was similar to the procedure of second step, the only difference being PCM application. Steady-state conditions were achieved in 50 minutes, during this period fan was not powered on. As it is the property of PCM to absorb heat and then release it with change in phase, hence it was used to enhance heat extraction. Stored heat was released as fan was powered on resulting in decrease of ambient temperature on the inside of tertiary shell and consequently a decrease in temperature of liquid PCM resulting in solidification of paraffin wax. The latent heat stored by the paraffin during phase change from solid to liquid contributed by adding accumulated heat in the air stream. Readings were noted for this step and calculations based on those readings were conducted, and a comparison was made between results of this step and the previous step. The PCM filled between the shells enhanced heat transfer as per its properties. It was observed that the temperature at the fan outlet increased and consequently heat extraction efficiency increased as well.

In order to visualize the correctness of proposed design, during second step the kiln was divided into four sections each having length of 0.15 meter. To note down temperatures for different sections along the length of the kiln five test points were chosen. The temperatures were noted down using K-type probe thermometer. It was observed that the temperature for bare kiln averaged around 231.2 °C and with secondary shell 236.1 °C.

A small increase in kiln surface temperature as mentioned in tab. 3 was observed with secondary shell installation. The reason for this increase was that air-flow was not provided for the first 50 minutes. Later on as the steady-state conditions were achieved the blower was turned on, the kiln shell outer surface temperature became constant. This also proves the usefulness of the proposed secondary shell design which does not allow for continuous increase in temperature because of entrapped waste heat in the gap between the two shells.

Table 3. Kiln surface temperature

Kiln length [m]	Temperature for bare kiln [°C]	Temperature with secondary shell [°C]
Start	204.4	209
0.1524	252.4	258.1
0.3048	248.6	254.2
0.4572	252.9	258.5
0.6096	198.4	201

Results and discussion

The overall inner shell temperature increased by 4.9 °C and then became constant without varying further. This satisfy an important requirement of the industry by not varying kiln temperature which otherwise can affect the production process. The dimensionless numbers used in calculations for the current system have their values in accordance with the specified geometry of the prototype.

Recovered waste heat at various mass-flow rates was calculated. It can be shown in terms of percentage of total heat loss from bare kiln as shown in tab. 3. It was observed that heat extracted and mass-flow rate had a direct relation. By varying air speed optimal conditions for maximum heat extraction were found. The proposed system extracted as much as 79.6 % of the total heat loss, tab. 4.

Total heat due to radiation heat transfer is 318 W.

Main purpose of this research was to find out the effect of utilizing PCM on total heat extracted. By using the equation set devised for the proposed system calculation was carried out at varying flow rates. It can be seen in tab. 5 that by applying PCM around the secondary shell total heat extraction increased by a considerable amount. Waste heat recovery improved from 3% to almost 8% at comparable and similar flow rates.

Table 4. Heat extracted without the PCM application

Obs.	Outlet air temperature [°C]	Air speed [ms^{-1}]	Mass-flow rate [kgs^{-1}]	Heat extracted [W]	% Extraction
1	72.2	9.7	0.0347	1506	79.6
2	72.0	9.4	0.0337	1456	76.9
3	71.4	8.7	0.0312	1329	70.2
4	71.2	8.4	0.0312	1329	70.2
5	70.8	7.7	0.0270	1134	59.9

Table 5. Heat extracted after installation of PCM shell

Obs.	Outlet air temperature [ºC]	Air speed [ms^{-1}]	Mass-flow rate [kgs^{-1}]	Heat extracted [W]	% Extraction
1	74.2	9.7	0.0347	1611	85.1
2	75.4	9.4	0.0337	1605	84.8
3	73.6	8.7	0.0312	1429	75.5
4	73.3	8.4	0.0312	1420	75.0
5	71.9	7.7	0.0270	1191	62.9

Comparison developed for heat extracted at different mass-flow rates are graphically shown in figs. 4 and 5. It can be seen in fig. 5 corresponding to tab. 5 that at air speed of 9.7 m/s highest extraction percentage is achieved.

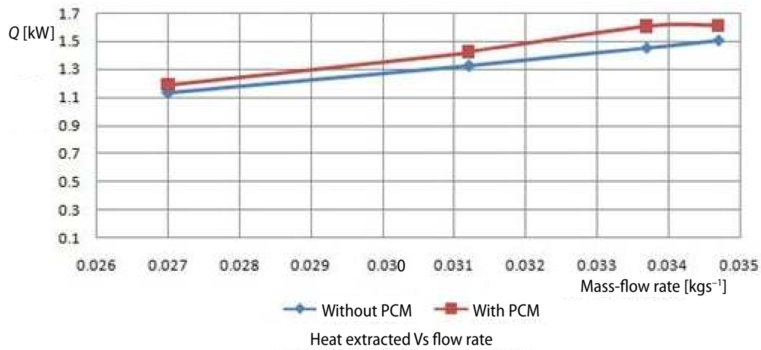

Figure 4. Heat extraction comparisons at different mass-flow rates

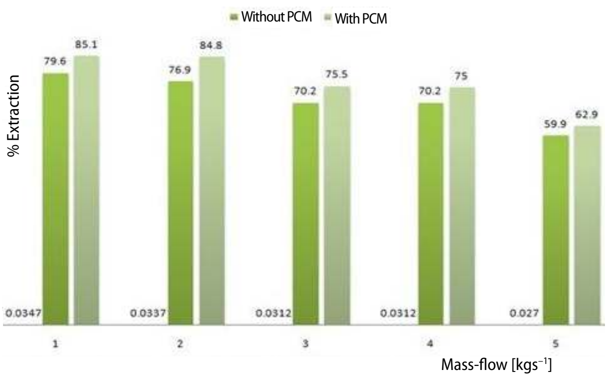

Figure 5. Percentage heat extracted with and without PCM

The results obtained for the prototype can be used for full sized rotary kilns. The proposed solution for waste heat recovery is backed by set of governing equations, which can be used for calculating heat loss and extraction for industrial kiln. Organic PCM application in such a set-up has proven to be of vital significance. Latent heat storing capability of paraffin wax enhanced heat extraction by first storing and then releasing the waste heat. It was also observed that paraffin wax PCM proved to be compatible with the prototype's material being non-corrosive, chemically, and thermally stable with no or little sub cooling.

Conclusion

This paper is focused on the experimental investigation of improved waste heat recovery through the surface of kiln using PCM. This paper is unique in its character as it has proposed the incorporation of paraffin wax as PCM in a multi-shell heat exchanger designed over a prototype of a rotary kiln. The improved waste heat recovery is experimentally demonstrated in the paper. The results obtained through presented equation set showed an improvement of almost 3-8% in heat extraction with the use of PCM. Moreover, the paper combines the waste heat recovery systems and PCM in one package and opened ways for using PCM for industrial purposes in waste heat recovery systems in order to make the current systems efficient and sustainable.

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Nomenclature

A – area of the outlet, [m^2]
A_k – area of the kiln, [m^2]
C_p – specific heatat consant pressure, [$kJkg^{-1}K^{-1}$]
g – acceleration due to gravity, [ms^{-2}]
h – convection heat transfer coefficient, [$Wm^{-1}K^{-1}$]
k – thermal diffusivity, [m^2s^{-1}]
L – characteristic length, (= D), [m]
l – length of kiln shell, [m]
$\dot{m}$ – mass-flow rate, [kgs^{-1}]
Nu – Nusselt number, [–]
Pr – Prandtl number, [–]
Q_{kiln} – heat loss from the surface pf bare kiln, [W]
Q_{conv} – convection heat transfer, [W]
Q_{rad} – radiation heat transfer, [W]
Q_{out} – total heat extracted, [W]
Ra – Rayleigh number, [–]
r – radius of the kiln shell, [m]
t – temperature, [K]
V – velosity of the air, [ms^{-1}]

Greek symbols

β – coeficient of thermal expansion, [K^{-1}]
ε – emissivity of the surface, [–]
ν – kinematic viscosity, [m^2s^{-1}]
ρ – densitiy of the air, [kgm^{-3}]
σ – Stefan Boltzmann constant, [$Wm^{-2}K^{-4}$]

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