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An Experimental Analysis of Waste Heat Recovery Potential from A Rotary Kiln of Cement Industry

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ABSTRACT

Cement production has been one of the most energy intensive processes in the world. Kilns serve as an integral part to produce clinker which is a tool to measure capacity of system. The temperature inside the kiln rises to 1400-1600 °C while its surface temperature is between 200-400 °C. The thermal efficiency of a kiln is about 55-60% and the remaining heat is lost in the form of flue gases and radiated from the surface. The current study has been carried out at a cement plant in Pakistan for the assessment of waste energy recovery from the surface of a rotary kiln. An experimental setup of small scale waste heat recovery with water heat exchanger has been fabricated at the plant site equipped with necessary instrumentation. Measurements of heat recovery are carried out at different water mass flow rates, surface temperatures, and transverse and radial distances of kiln. Results revealed that maximum water temperature achieved was 25 °C at 1.8 kg/min mass flow rate of water at kiln surface temperature of 320 °C. The distance of kiln and heat recovery unit is 380 mm where maximum potential from kiln surface is estimated to be 3.13 kW/m^2. Thus, the current study proved significant waste heat recovery potential from kiln shell of a cement industry which can be further utilized for any on-site application.

Keywords: *Waste heat recovery, Kiln, Heat Recovery System, Experimental Analysis, Cement industry*

1. Introduction

Cement production industry is one of the most energy intensive industries in the world. In order to manufacture/produce clinker, rotary kilns are used. In cement industry, 51% of the total input energy is lost in the form of hot flue gases, (a) 24.4% from exhaust stacks, (b) 15.61% from kiln surface (convection plus radiation) and 11% heat is utilized in the system. Cement plants having capacity of 600 tons/day-clinker, accounts for 4 MW thermal energy from the surface of a kiln [1]. In a study, it was indicated that the heat loss in the burning zone of rotary kiln is about 49% of the total heat lost from the surface of kiln [2]. Another research calculated that the heat loss is around 26.35% from the surface of a kiln and 19% through exhaust gases. To decrease/recover heat loss annular ducts around the kiln surface have been suggested. It captures the convective and radioactive heat, decreasing the fuel consumption of kiln to 12%, and increasing its energy efficiency up to 3.81% [3].

In another study, it was found that the specific energy consumption for clinker was 3735.45 kJ/kg. Thermodynamic analysis of the kiln showed that 11.3% of the total input energy was lost from the surface of the kiln [4]. Atmaca and Yumrutas [4] also suggested that heat losses from the surface can be minimized by the formation of anzast layer inside the rotary kiln. It can also be decreased by utilization of high quality magnesia spinel and high alumina refractory bricks inside the kiln, which causes 7.27% reduction in energy consumption corresponding to a saving of 271.78 MJ per ton of clinker production [4]. Similar research about heat loss showed that 51% of the total input heat was wasted, which accounts for 217.31 GJ heat for 600 tons/day-clinker capacity cement plant. It was also suggested that during the recovery of waste heat, no surface contact with almost zero forced flow from the surface of rotary kiln were needed [5]. Temperature of the air between the surface of the rotary kiln and the heat recovery system was 150 °C [5]. It was determined that the kiln stacks exit gases and kiln surface were the major sources of thermal energy losses, amounting to 27.9% (1216.75 kJ/kg) and 10.84% (472.56 kJ/kg), respectively [5]. Waste heat recovery steam generator (WHRSG) and secondary kiln shell were considered, which account for savings of 42.88 MWh/year and 5.30 MWh/year, respectively. Waste heat recovery units reduce the emission of greenhouse gases up to 14.10% [6].

Caputo et al. [7] found that heat losses from the kiln surface was 8 to 15%. After applying recovery heat exchanger around the kiln, 1700 to 2500 kW heat was recovered from 20 m long kiln [7]. Jamali and Noorpoor [8] proposed new heat recovery system (based on renewable energy) for the cement plant. Their integrated system generated 18.4 MW and 17.4 MW electricity during winter and summer season, respectively.

In various studies, researchers analyzed different flow configurations in heat exchangers, selection of material for heat exchanger tubes, design parameters of heat exchangers and different modes of heat transfer [9-11]. Similarly, a research work showed the heat recovery techniques at different temperature ranges, utilization of direct heat and use of heat pump [12]. Another study showed the effect of temperature, phase and chemical composition of the exhaust stream on heat recovery unit, along with the discussion about low temperature heat exchangers [13]. Researchers have also proposed different design steps of heat exchanger to recover surface heat [14]. Radiation and convection heat loss from the

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surface of a kiln has the potential for drying faecal sludge and this dried fuel can fulfill 2% of daily energy requirement of the plant [15]. Furthermore, it was also proposed that a secondary shell with water circulating tubes around the existing kiln shell can have a potential to save up to 73% of heat loss [15]. In another study, authors presented the energy and energy analysis of a rotary kiln and calculated that energy and exergy efficiency are 69% and 16%, respectively [16]. This report described the heat losses from different stages of cement manufacturing and also discussed that the heat loss from the kiln shell was 0.09 to 0.5 MBtu/ton of clinker (94500 to 527527kJ/ton). It is also pointed out that main losses occurred in the burning zone of a rotary kiln. Additionally, it was proposed that utilizing better insulating refractory and high temperature insulating linings for the kiln refractory can reduce fuel use by 0.1- 0.34 MBtu/ton [17].

In view of above literature, it can be concluded that experimental work for waste heat recovery from the kiln is rarely performed. Therefore, the current study is mainly focused on experimental analysis of waste heat recovery from the surface of a rotary kiln of BESTWAY Cement Plant having 3300 ton/day capacity located in Pakistan. The study indicates the available potential of waste heat recovery in terms of achieved water temperature and heat absorbed based on kiln surface temperature along the length of the kiln.

2. The System Description and Overall Available Heat Recovery Potential

The design parameters of the rotary kiln used in this study are mentioned in Table 1. Surface temperature of the kiln (T_s) varies along the horizontal axis of the kiln. Due to temperature variations the kiln is divided into three zones along the horizontal axis, i.e., high temperature zone (0 to 19 m (zone-1)), intermittent temperature zone (20 to 38 m (zone-2)) and low temperature zone (39 to 57 m (zone-3)). Each zone area is 238.64 m^2.

Table 1: Design parameters of kiln.

Parameter	Value
Diameter of Kiln	4 m
Length of Kiln	57 m
Kiln Inclination	2°
Rotation speed	5 rpm
Surface area of Kiln	715.92 m^2

In the kiln, three modes of heat transfer are involved. Heat transfer from the inside of the rotary kiln to outer surface is through conduction and from the outer surface to the atmosphere is through convection and radiation as presented in Fig. 1.

Rate of conduction heat transfer is calculated using Eq. (1).

$$q_x = -k\frac{dt}{dx} \quad (1)$$

Rate of convection heat transfer is determined by Eq. (2) [15].

$$q'' = h_c(T_s - T_\infty) \quad (2)$$

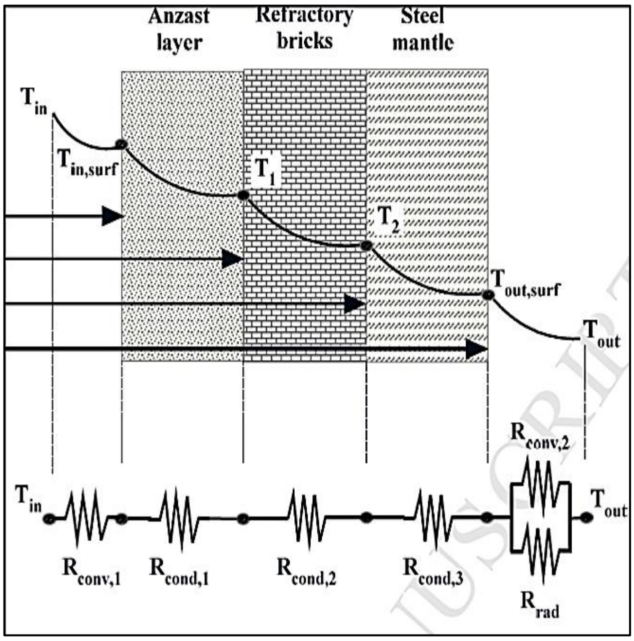

Fig. 1: Modes of heat transfer at rotary kiln [4].

Where q (*W/m²*) is heat flux, T (*K*) is temperature, h (*W/m². K*) is convection heat transfer coefficient, k (*W/(m. K)*) is thermal conductivity.

Convection heat transfer is a function of the Reynolds Number, Prandtl Number and the Nusselt Number. For the determination of kinematic viscosity (v), thermal conductivity (k) and the Prandtl No. (Pr), average of kiln surface temperature and ambient temperature is used. At mean temperature, kinematic viscosity (v), thermal conductivity (k) and Prandtl No. (Pr) are obtained from the work by Cengel [18] along with typical values of heat transfer coefficient.

Nusselt number is used to determine the heat transfer co-efficient between solid body and the moving fluid, using Eq. (3).

$$h = N_u D_{kiln}/k \quad (3)$$

Heat transfer co-efficient due to thermal radiation is obtained by Eq. (4).

$$h_r = \in \sigma \frac{Ts^4 - Ta^4}{Ts - Ta} \quad (4)$$

The total heat transfer coefficient h_{total} is the heat which is transferred through convection and radiation from the surface of a rotary kiln, h_{total} is determined using Eq. (5).

$$h_{total} = h_r + h_c \quad (5)$$

Total heat available from the surface of a rotary kiln is determined by Eq. (6).

$$Q = hA(T_s - T_a) \quad (6)$$

Values of Reynolds No. (R_e), Nusselt. No. (N_u), radiation heat transfer coefficient (h_r), convection heat transfer coefficient (h_c) and heat transfer potential available for each zone are given in Table 2.

Table 2: Design parameters for potential assessment of Kiln.

Length (m)	Area (m^2)	T_s (°C)	T_a (°C)	$(T_s\text{-}T_a)/2$ (°C)	R_e	N_u	h_r (W/m². °C)	h_c (W/m². °C)	$h=h_r+h_c$ (W/m². °C)	Q (MW)
0-19 Zone-1	238.6	305	30	167.5	1.08×10^5	268	18.1	3.25	21.35	1.33
20-38 Zone-2	238.6	295	30	162.5	1.13×10^5	281	16.4	3.30	19.70	1.24
39-57 Zone-3	238.6	217	30	123.5	1.59×10^5	369	11.9	2.99	14.89	0.67

3 Experimental Setup

3.1 Construction of Heat Recovery System and Sensor Installation

In this research a small scaled heat recovery system is used to capture the heat from the surface of a rotary kiln. Fig. 2 shows the schematic view of the heat recovery system. The heat recovery system is installed at the bottom of the rotary kiln. This is because of kiln structure in term of rotational segments, which allow to install the heat recovery system only on feasible location, to avoid any obstruction to the rotation. Also w.r.t. heat transfer, uniform heat flux normally exists around the shell. The heat recovery system consists of a main frame made up of mild steel pipe, sheet and the copper tubes. Main frame is joined with arc welding. Copper tubes are used for heat recovery system due to its high thermal conductivity. Copper tubes were bent with tube bender and these tubes are clamped on the main frame. Flexible rubber pipes are fastened with copper tubes; these pipes are used as inlet and outlet supply of water to the heat recovery system. Water flow regulator is installed at the inlet line to vary the mass flow rate of water. Design values of heat recovery system are mentioned in Table 3.

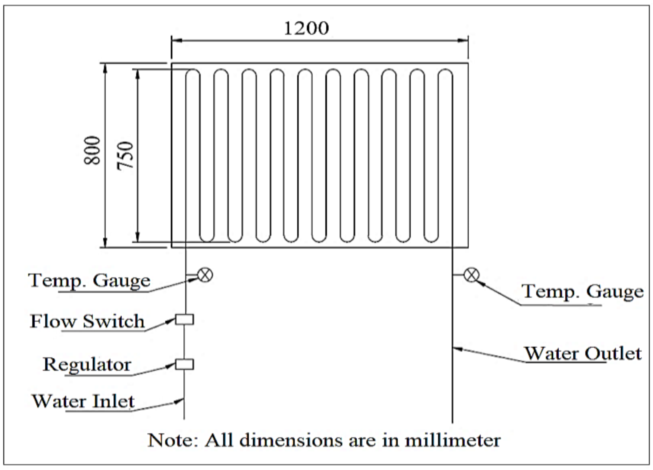

Fig. 2: Schematic of heat recovery system.

Temperature gauges are installed at the inlet and outlet section of the heat recovery system for the measurement of water temperature. A mass flow meter is installed at the inlet of the heat recovery system. Kiln shell scanner is installed to collects the temperature of the rotary kiln along the horizontal axis. The scanner image is shown in Fig. 3. The highlighted

Table 3: Design values of heat recovery system.

Parameters	Value
Main frame size	800 x 1200 mm
Mild steel sheet thickness	1 mm
Mild steel sheet size	800 x 1300 mm
Copper tube diameter	10 mm
Wall thickness	1 mm
Copper tube outer diameter	12 mm
No of passes	19 Nos.
Lengths of each pass	740 mm
Total area of heat exchanger tubes	0.44 m^2
Water Pump Capacity	220 m^3/hr

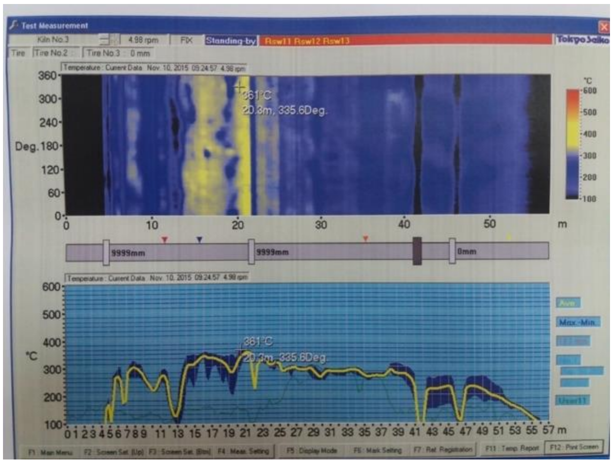

Fig. 3: Kiln scanner view showing temperature variations.

section indicates the region considered in this study. Velocity flow meter is used for the measurement of velocity of air.

Infrared temperature gun is also used for temperature measurements. Infrared temperature ranges from 0-1000 °C with an accuracy of $\pm$ 0.1°C. Temperature gauges ranges from 0-300 °C with an accuracy of $\pm$ 1 °C. Temperature gauges are tested and calibrated with an ISO tested thermometer. Kiln shell scanner ranges from 0-1000 °C with an accuracy of $\pm$1°C. Air velocity flow meter (Type: KIMO DP2000 M) data measurement ranges from 0-35 m/sec with accuracy of $\pm$ 0.1m/sec. The heat recovery system is installed under the rotary kiln. The schematic and actual views of

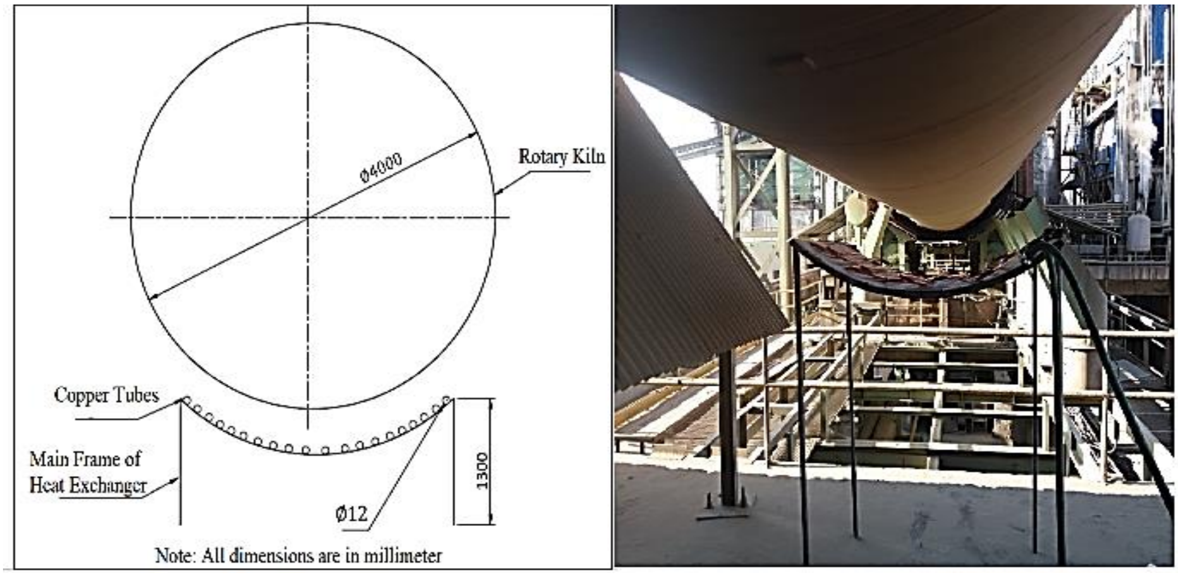

Fig. 4: Schematic and actual views of experimental setup.

Experimental setups are shown in Fig. 4. Due to various limitations on the surface of kiln in terms of bearing and other supporting items, only a small scaled heat exchanger is installed at an appropriate location. It is worth mentioning that internal burning and heat transfer mechanism were not altered as experiments were performed during routine operation; therefore, quality of cement is not compromised. The initial cost of this small prototype heat recovery system is approximately Pk. Rs. 55000/-. The operating cost of the proposed system is Pk. Rs. 30000/annum.

3.2 Measurement Procedure

Experiments were carried out during the months of April and May on selected days. After the installation of heat exchanger, water flow was adjusted from flow regulator. Data collection was started once the heat exchanger gained steady state condition. Measurements were taken along different length of heat exchanger both horizontally and radially, at different water flow rates. The data were collected at different kiln locations and at various kiln surface temperatures. Experimental results vary with variation in kiln surface temperature. Moreover, variation in water outlet temperature was observed with change in mass flow rate of water. During measurements, each reading was recorded at an interval of 40 min so that heat exchanger can achieve steady state conditions.

Data was collected from the heat exchanger with and without black paint effect. Then heat exchanger surfaces, i.e., copper pipes and the main frame were coated with black paint. Black paint coating increased the heat absorption and reduced heat reflection.

4. Results and Discussion

In the present study we have investigated the effects of radiative (h_r) and convective (h_c) heat transfer coefficient and total potential (Q) on different surface temperatures along the length of kiln. On the basis of surface temperature, kiln is divided into three zones along the horizontal axis: zone-1 from 0-19 m, zone-2 from 20 to 38 m and zone-3 from 39 to 57 m. It is evident that the kiln surface temperature is highest in the burning area, in zone-1 (0-19 m), and decreases in zone-2
(20-38 m) and is lowest in zone-3 (39-57 m). The effect of kiln surface temperature on the coefficient of radiation and convection is shown in Fig. 5. It is noted that coefficient of convection and radiation are maximum at high surface temperature and decrease with reduction in kiln surface temperature.

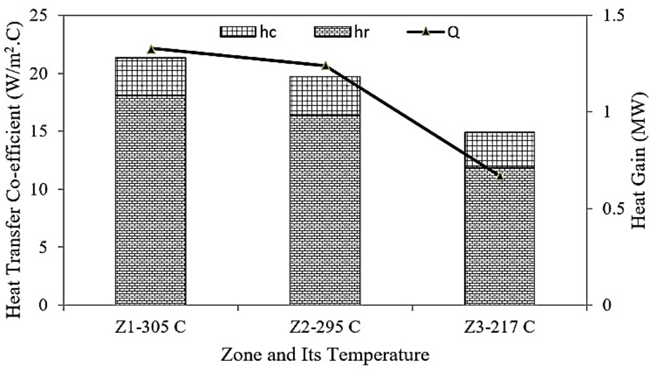

Fig. 5: Effect of temperature on coefficient of radiation and convection.

4.1 Experimental Analysis

Experiments were carried out at Bestway Cement Limited and work was performed at three different locations along the longitudinal and radial axis of the kiln. Positions 1, 2 and 3 are at 39 m, 37 m and 35 m, respectively along the horizontal axis ahead of kiln entry as shown in Fig. 6. These positions were selected due to lower variations in temperature as shown in Fig. 3. The radial positions are at C_1 = 380 mm, C_2 = 500 mm and C_3 = 600 mm.

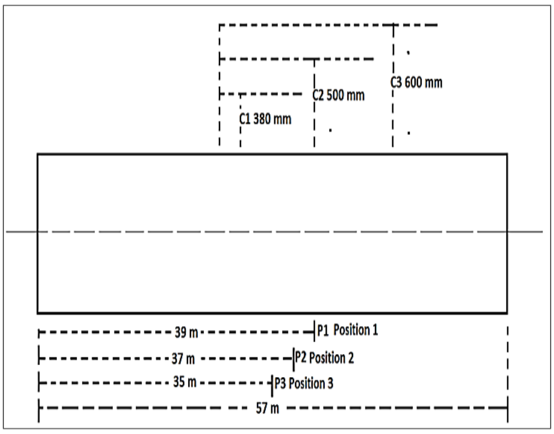

Fig. 6: Top view of Kiln, showing three horizontal points locations (positions) and radial distances from kiln surface.

Effect of mass flow rate on water outlet temperature of heat exchanger is depicted in Fig. 7. It has been observed that at lower mass flow rate (1.8 kg/min), water outlet temperature was 53 ºC at C_1 and P_1. With the increase of mass flow rate, water outlet temperature decreased at the same radial distance. It is concluded that water outlet temperature is inversely related to the mass flow rate for the same radial distance. For same P_1, water outlet temperature decreases from C_1 to C_3. This means that water outlet temperature is also inversely related to the distance of the heat recovery device from the surface of the kiln. The same trend is observed as moved from position 1 to position 3 along radial distances. Minute difference in temperature has been recorded from position 1 to 3 at the same corresponding radial distances. It is concluded that by increasing the mass flow rate of water, outlet temperature of water decreases as we move from P_1 to P_3 and from C_1 to C_3.

The temperature difference (ΔT) is another important design parameter for evaluating the efficiency of the system. At a single position, difference in water temperature is higher at low mass flow rate at constant radial distance and it decreases by increasing the mass flow rate of water. Observing the values of difference in water temperature from C_1 to C_3, keeping the position constant, it is concluded that ΔT decreased at constant mass flow rate of water as shown in Fig. 8.

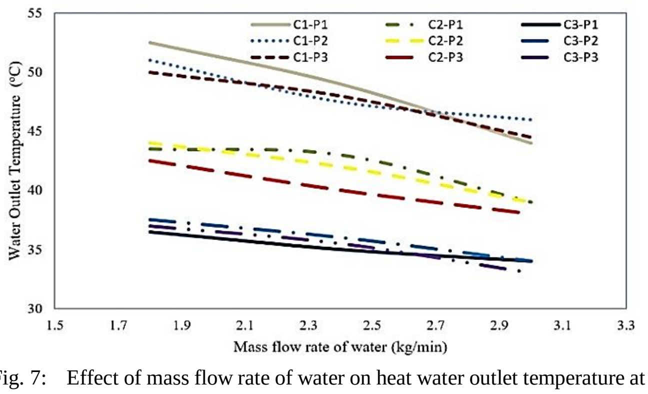

Fig. 7: Effect of mass flow rate of water on heat water outlet temperature at heat recovery device at positions 1, 2 and 3 on corresponding radial distances.

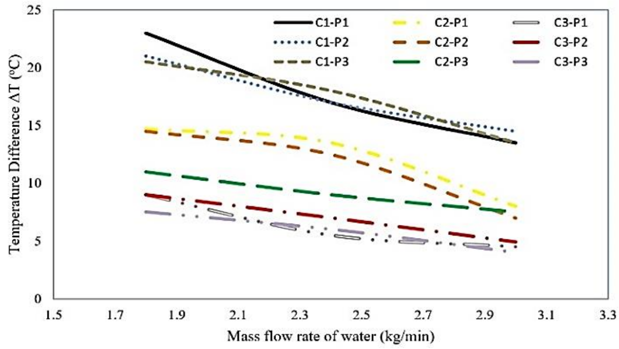

Fig. 8: Effect of mass flow rate of water on temperature difference at positions 1, 2 and 3 on corresponding radial distances.

Difference in water temperature depends on the kiln surface temperature. To investigate this, experiments were carried out to check the effect of ΔT on kiln surface temperature at three radial distances (Fig. 9). As surface temperature of kiln is increased, water temperature difference increases. At 1.8 kg/min, temperature difference is comparatively higher than other corresponding mass flow rate at constant radial distance. As mass flow rate of water increases, the temperature difference at constant radial distance decreases. At a constant mass flow rate (1.8 or 2.4 or 3 kg/min), temperature difference will decrease as we move from C_1 to C_3. To conclude, the surface temperature will automatically decrease by increasing the distance of the heat exchanger from the kiln.

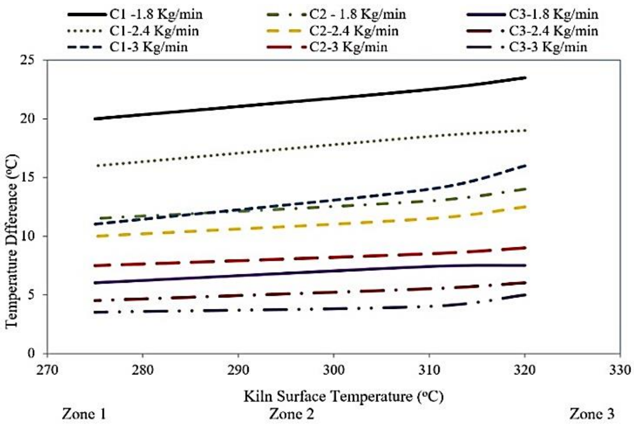

Fig. 9: Effect of kiln surface temperature on temperature difference at (a) 1.8 kg/min (b) 2.4 kg/min (c) 3 kg/min.

In view of high radiation heat losses, the experimental procedure was improved further by applying black coating material on the copper tubes of the heat exchanger. Water outlet temperature at different mass flow rate after black coating of surface is depicted in Fig. 10. Increase in water outlet temperature is observed after black coating with mass flow rate of water. At 1.8 kg/min, the temperature difference of C_1 increased up to 55 ºC from 53 ºC, which was recorded when surface was uncoated. It is concluded that surface black coating increases the temperature difference up to 1 to 2 ºC. Fig. 10 shows a comparison of outlet temperature with and without application of black coating on the surface. Increase in water outlet temperature is observed after black coating with mass flow rate of water. Around 1 to 2 ºC rise is observed in C_1, which is 380 mm from the heat exchanger. Fig. 11 shows the effect of water outlet temperature versus mass flow rate of water at positions 1, 2 and 3. Finally, it can be concluded that heat absorption is enhanced due to coating which caused further recovery of radiation heat losses from the kiln.

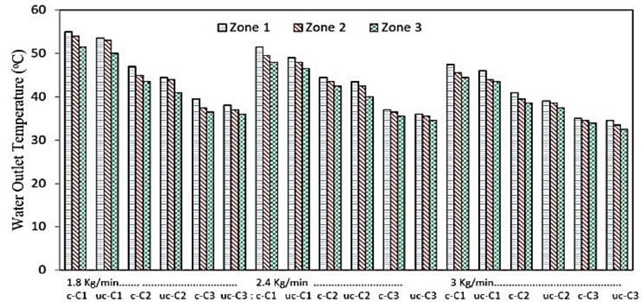

Fig. 10: Water outlet temperature of different zones against different mass flow rates: c = coated, uc = uncoated.

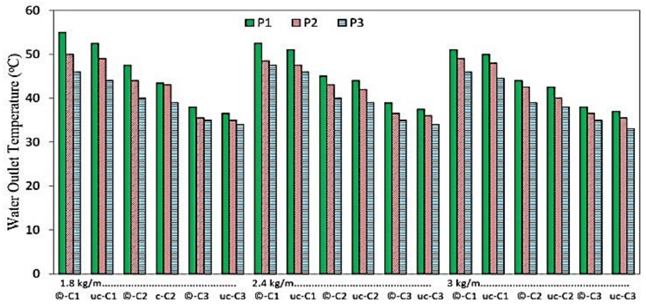

Fig. 11: Water outlet temperature at different positions against different mass flow rates: c = coated, uc = uncoated.

5. Conclusions

In the current study, energy recovery potential from the waste heat of a rotary kiln at Bestway Cement Limited, Pakistan was experimentally analyzed under varying water flow rate and positions along transverse and radial axis under both coated and uncoated scenarios. It has been observed that maximum heat flux potential from the kiln surface is about 3.13 kW/m^2 at surface temperature of 320 ℃. Furthermore, it was found that heat exchanger outlet temperature is highest at low mass flow rate, i.e., at 1.8 kg/min mass flow rate of water outlet temperature is 55 ºC; whereas at 2.4 and 3 kg/min mass flow rates water outlet temperatures become 47 ºC and 38 ºC, respectively. In addition, water outlet temperature depends upon the kiln surface temperature. High outlet temperature of water is observed at high surface temperature of kiln, i.e., at 320 ºC; surface temperature of kiln resulted in 55 ºC outlet temperature of water and the value of temperature decreases to 50 ºC at the kiln surface temperature of 275 ºC.

It was also observed that high heat recovery is achieved at minimum radial distance of the heat recovery system from the kiln surface. Additionally, about 4% higher temperature gains are achieved with black coating on the surface of copper pipes. Future study can be extended to develop economic analysis of waste heat recovery potential from rotary kiln and mapping with actual loading of the cement industry. For future work, the scalability of the system can be altered by introducing multiple segments. These studies can also include the end application of the proposed system w.r.t. chiller or space heating.

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