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A Mathematical Modelling and Simulation for Reduction in Thermal Losses by Painting DRI Kiln

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Abstract **- Rotary Kilns has been widely used for processing minerals, producing cement, calcining of rotary kilns consume energy intensively. Therefore it is desired to assess the thermal losses from the kiln surface and find a way to reduce the energy losses. The paper gives an insight in the mathematical modelling of rotary kiln of a DRI Plant to investigate the savings by painting the kiln outer surface with low-emissivity paint. However, it must be carefully evaluated the insulation effect of the paint because good insulation will increase the metal shell temperature. Too much temperature increase could result in structural problems induced by differential thermal expansion between the shell metal and the refractory bricks.**

In this paper, heat transfer analysis is conducted to help make a decision concerning paint selection and the potential consequence of painting the kiln surface. The paint emissivity has a significant effect on the kiln surface heat transfer. Lower emissivity paint decreases thermal losses but increases the kiln surface temperature. A commercial available paint with the emissivity of 0.65 is selected to achieve the optimum result of an energy saving of 369 kW without imposing detrimental destruction to the refractory brick's integrity inside the kiln. The amount of saving can increase if around emissivity of 0.5 can be selected but the availability of the quality of paint is another concern. Moreover with this emissivity, the reduction in coal consumption is around 3000 kg/day with an energy saving of 668kW.

Keywords: Kiln, Paint, Shell temperature, Thermal losses.

I. INTRODUCTION

Rotary kiln is a pyro-processing device used to raise materials to a high temperature (calcination) in a continuous process. Rotary Kilns has been widely used for processing minerals, producing cement, calcining petroleum cokes, sponge iron or drying biomass and wastes. The kiln is a cylindrical vessel, inclined slightly to the horizontal, which is rotated slowly about its axis. The material to be processed is fed into the upper end of the cylinder. As the kiln rotates, material gradually moves down towards the lower end, and may undergo a certain amount of stirring and mixing. Hot gases pass along the kiln, sometimes in the same direction as the process material (co-current), but usually in the opposite direction (counter-current).

The hot gases may be generated in an external furnace, or may be generated by a flame inside the kiln. Such a flame is projected from a burner-pipe (or "firing pipe") which acts like a large Bunsen burner. The fuel for this may be gas, oil, pulverized petroleum coke or pulverised coal.

Fig 1. Rotary Kiln

I.1 Construction: The basic components of a rotary kiln are the shell, the refractory lining, support tyres and rollers, drive gear and internal heat exchangers.

I.1.1 Kiln Shell: This is made from rolled mild steel plate, usually between 15 and 30 mm thick, welded to form a cylinder which may be up to 230 m in length and up to 6 m in diameter. This will be usually situated on an east/west axis to prevent eddy currents. Upper limits on diameter are set by the tendency of the shell to deform under its own weight to an oval cross section, with consequent flexure during rotation. Length is not necessarily limited, but it becomes difficult to cope with changes in length on heating and cooling (typically around 0.1 to 0.5% of the length) if the kiln is very long.

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I.1.2 Refractory Line: The purpose of the refractory lining is to insulate the steel shell from the high temperatures inside the kiln, and to protect it from the corrosive properties of the process material. It may consist of refractory bricks or cast refractory concrete, or may be absent in zones of the kiln that are below around 250°C. The refractory selected depends upon the temperature inside the kiln and the chemical nature of the material being processed. In some processes, such as cement, the refractory life is prolonged by maintaining a coating of the processed material on the refractory surface. The thickness of the lining is generally in the range 80 to 300 mm. A typical refractory will be capable of maintaining a temperature drop of 1000°C or more between its hot and cold faces. The shell temperature needs to be maintained below around 350°C in order to protect the steel from damage, and continuous infrared scanners are used to give early warning of "hot-spots" indicative of refractory failure.

I.1.3 Tyres & Rollers: Tyres, sometimes called riding rings, usually consist of a single annular steel casting, machined to a smooth cylindrical surface, which attach loosely to the kiln shell through a variety of "chair" arrangements. These require some ingenuity of design, since the tyre must fit the shell snugly, but also allow thermal movement. The tyre rides on pairs of steel rollers, also machined to a smooth cylindrical surface, and set about half a kiln-diameter apart. The rollers must support the kiln, and allow rotation that is as nearly frictionless as possible. The mass of a typical 6 x 60 m kiln, including refractory's and feed, is around 1100 tonnes, and would be carried on three tyres and sets of rollers, spaced along the length of the kiln. The longest kilns may have 8 sets of rollers, while very short kilns may have only two. Kilns usually rotate at 0.5 to 2 rpm, but sometimes as fast as 5 rpm.

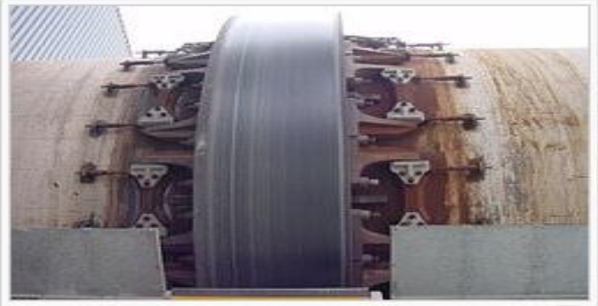

Fig 2: Kiln tyre showing typical chair arrangement

I.1.4 Drive Gear & Internal Heat Exchanger: The kiln is usually turned by means of a single Girth Gear surrounding a cooler part of the kiln tube, but sometimes it is turned by driven rollers. The gear is connected through a gear train to a variable-speed electric motor. This must have high starting torque in order to start the kiln with a large eccentric load. A 6 x 60 m kiln requires around 800 kW to turn at 3 rpm. The speed of material flow through the kiln is proportional to rotation speed, and so a variable speed drive is needed to control it. Heat exchange in a rotary kiln may be by conduction, convection and radiation, in descending order of efficiency. In low-temperature processes, and in the cooler parts of long kilns lacking pre-heaters, the kiln is often furnished with internal heat exchangers to encourage heat exchange between the gas and the feed.

I.2 Flow Process :

The flow process for a typical sponge iron and electricity production via rotary kiln is shown in figure below:-

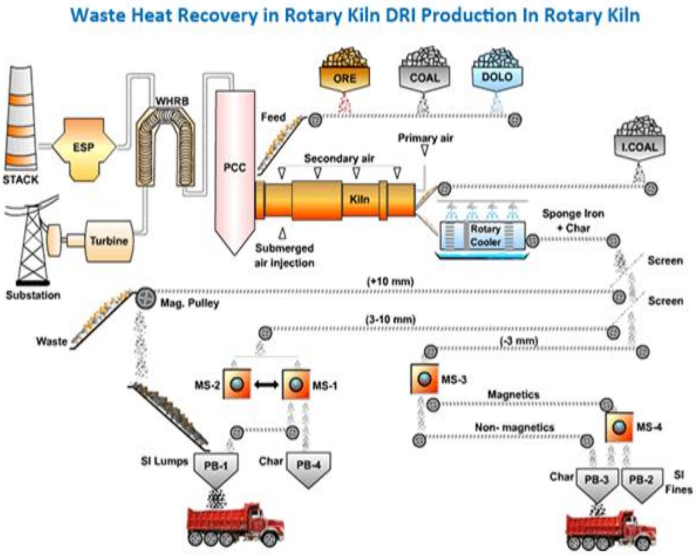

Fig 3: Sponge iron production in DRI rotary kiln

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II. GEOMETRY AND BOUNDARY CONDITIONS

The geometry shown in fig 4 shows the overall dimension of the kiln considered for the paper.

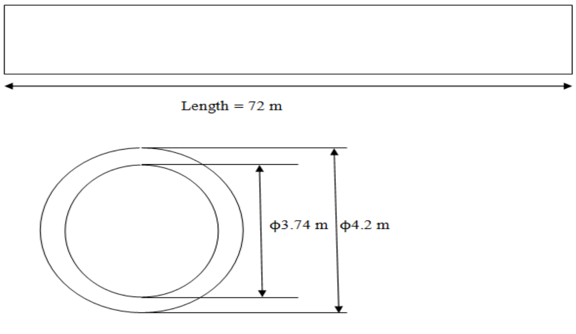

Fig 4: Length and cross-section of rotary kiln

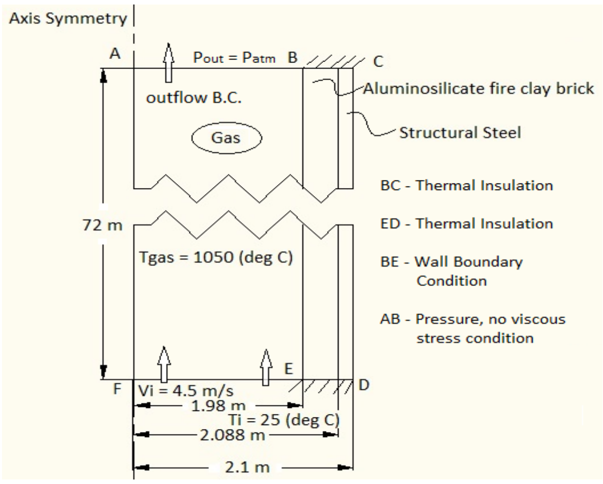

Fig 5: Boundary condition for rotary kiln

The refractory brick considered is Aluminosilicate fire clay brick of outer radius of 2.088m and inner radius of 1.98m. The lining is covered with structural steel over which there is a lining of structural steel 12mm. The different properties considered for the brick lining and steel are assumed to be function of temperature. The model has been assumed as 2-D axisymmetric as shown in Fig 5 with hot gases inside the kiln is modelled as air at high temperature. The different properties of air are assumed as function of temperature and pressure in the simulation process.

III. MODELLING AND ANALYSIS

The main aim is to estimate the thermal losses from the kiln surface under the existing situation, and then evaluate the thermal losses after painting the surface with the low emissivity paint. The difference between the thermal Losses with and without the paint will be where the potential energy savings will exist. The surface temperature increase due to the application of paint is calculated. Thermal losses from the kiln surface are calculated by considering natural convection as well as thermal radiation. The analysis has been done in the COMSOL Multiphysics Software and the related results have been shown subsequently..

Hot gases inside the kiln

Initial Condition

$T_i = 25^oC$, P_i =101325Pa and V = 0 m/s

Momentum equation for fluid inside the kiln

$$\rho(u.\nabla).u = \nabla[-pl + \mu(\nabla u + (\nabla u)^T) - \frac{2}{3}\mu(\nabla.u)l] + F$$

$$\nabla.(\rho u) = 0$$

The inlet velocity of air is considered at 4.5m/s and at the outlet pressure, no viscous stress condition has been considered

Energy Equation

$$\rho C_p u \nabla T = \nabla.(k\nabla T) + Q + Q_{vh} + W_p$$

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Inlet temperature=25°C

The inner wall of the kiln is assumed to be at temperature of 1050°C and the heat will be conducted through the layers of the kiln and will be given out through natural convection and radiation at the outer surface.

At CD

$$-n.(-k\nabla T) = h.(T_\infty - T)$$

$$T_\infty = 300K$$

$$-n.(-k\nabla T) = \varepsilon.\sigma.(T_\infty{}^4 - T^4)$$

At the outlet, outflow boundary condition is assumed and the initial temperature of refractory and steel temperature is 25°C.

Kiln Layers

In the layers of the kiln, the energy equation is given by

$$\rho C_p u.\nabla T = \nabla.(K\nabla T) + Q$$

Mesh statistics

Property	Value
Minimum element quality	0.1291
Average element quality	0.8107
Triangular elements	48626
Quadrilateral elements	1022
Edge elements	9373
Vertex elements	8

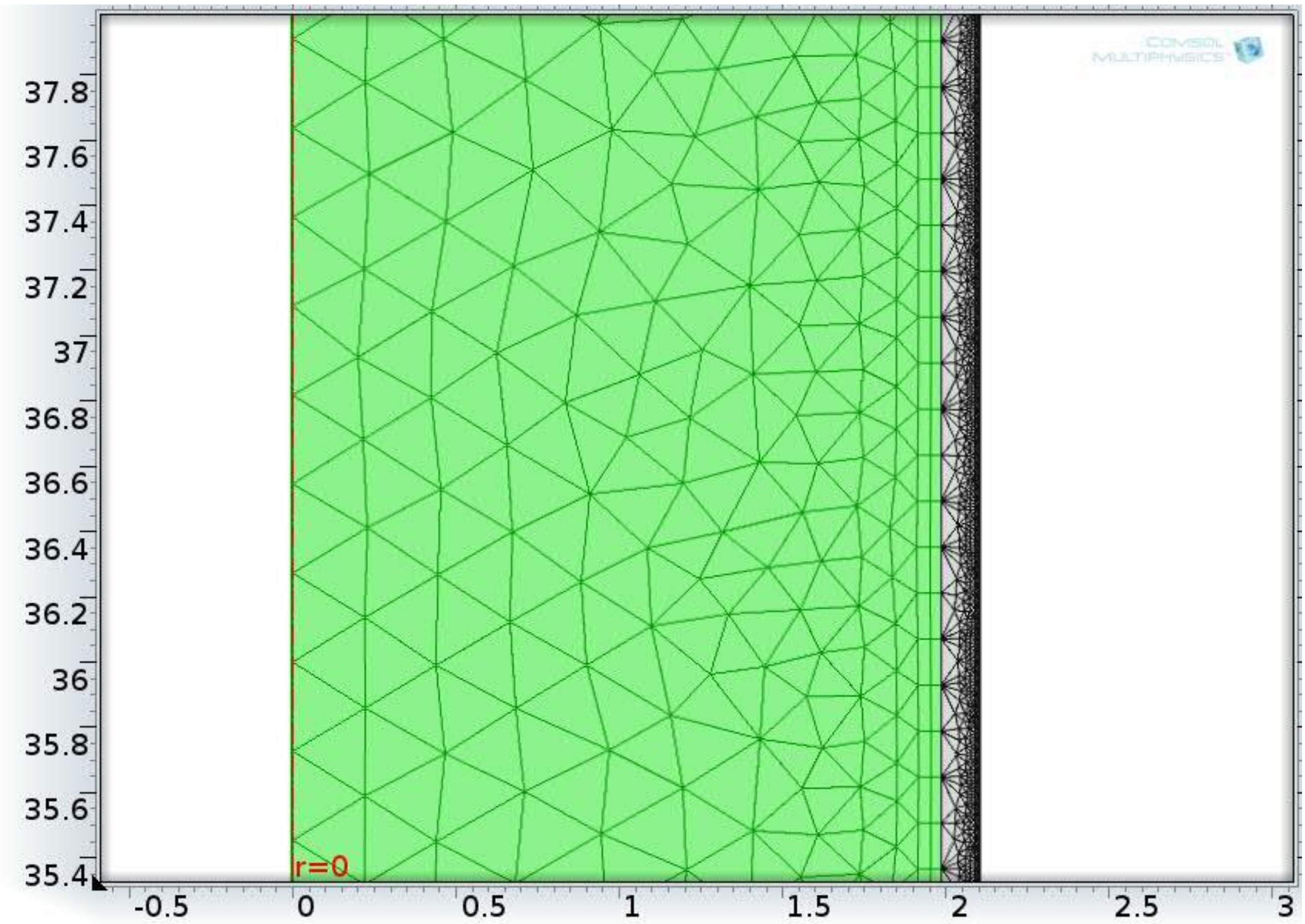

Fig 6 Mid portion of the Kiln with meshing

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IV METHODOLOGY AND RESULTS

The schematic of rotary kiln is shown in Fig. 7 where temperatures T-1 to T-12 are noted through 12 thermocouples which are placed along the length. The values measured through thermocouples give temperature profile in the rotary kiln. Around the periphery of the kiln air is injected through positions AT-1, AT-2, AT-3, MF-1 and MF-2. At AT-1 to AT-3 positions three blowers are attached. At MF-1 and MF-2 two blowers are placed to each inlet. Thus, total seven blowers are placed which provide air along the length of the kiln. The temperature readings gives information for an average temperature to be considered inside the kiln. To produce sponge iron, iron ore and coal are used as raw material. In the kiln, coal is injected from feed side, which is called feed coal as well as discharge side, which is called injected coal. Injected coal is fed as fines, medium and coarse coal pneumatically however, feed coal is fed as coarse coal [1]. Due to limitation of pages of the paper data of 10 hours of day one is shown in Table I.

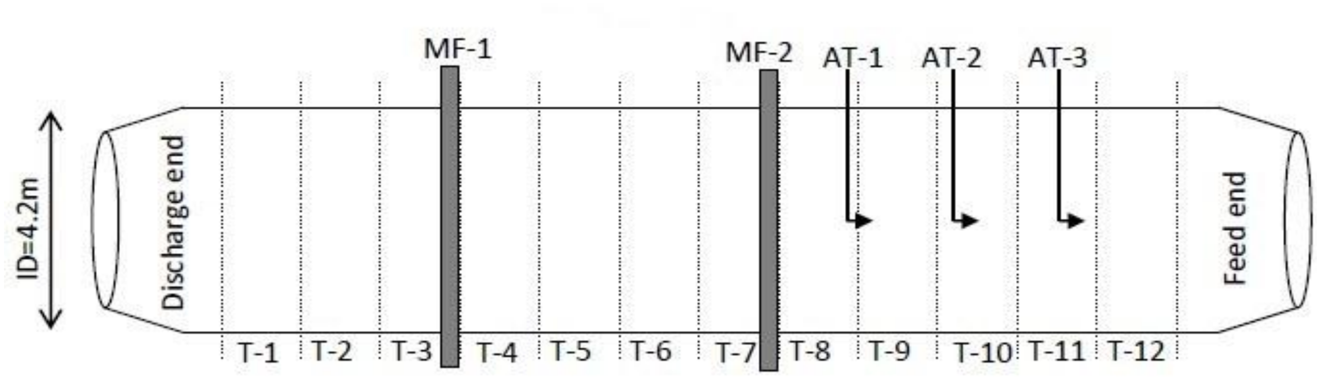

Fig 7 Schematic of Rotary Kiln with thermocouples

Table-I Temperature readings inside the Kiln

Temperature profile (°C)											
T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9	T-10	T-11	T-12
1098	1090	1085	1076	1075	1057	1061	1007	935	898	811	773
1100	1092	1087	1078	1061	1047	1044	1000	931	896	813	770
1076	1068	1063	1060	1061	1045	1051	1011	923	915	816	766
1076	1068	1063	1053	1060	1056	1075	1011	938	923	816	784
1050	1042	1037	1034	1056	1061	1062	1029	943	927	831	770
1040	1032	1027	1035	1055	1062	1070	1030	940	934	844	775
1059	1051	1046	1026	1060	1066	1065	1039	965	934	867	793
1054	1046	1041	1029	1059	1060	1074	1041	967	963	869	795
1075	1067	1062	1048	1073	1073	1076	1048	978	965	876	796
1086	1078	1073	1055	1083	1089	1082	1070	986	960	865	791

The basic procedure in this study is to estimate the thermal losses from the kiln surface under the existing situation, and then evaluate the thermal losses after painting the surface with the low- emissivity paint. The difference between the thermal losses with and without the paint will be where the potential energy savings will exist. The surface temperature increase due to the paint is calculated.

The heat transfer rate due to the natural convection on the outer surface can be obtained by:

$$Q_{conv} = h * A * \Delta T$$

where A is the area of heat transfer surface, and ΔT is the same temperature difference as in Eq. (1).

The radiative heat transfer from a surface with a temperature of T_w to the ambient with a temperature of T_0 is given by

$$E = \varepsilon * \sigma * F_{12} * ({T_w}^4 - {T_o}^4)$$

where ε is the surface emissivity and σ is the Stefan-Boltzmann constant ($5.67*10^{-8}$ W/m^2K^4).The temperatures in this equation need to be in Kelvin, and the surface needs to be gray (independent of radiation wavelength) and diffusive (independent of radiation direction). F_{12} is the view factor that takes into account the radiative heat flux effectively transferred between two surfaces. Ignoring the detailed structure, the kiln is modelled simply as a cylinder in this study, so the view factor is always 1. The surface is assumed gray and diffuse in all the calculations of this study. Multiplying the heat transfer density (E) by the surface area, the radiative heat transfer rate can be obtained.

$$Q_{rad} = A * E * \Delta T$$

Total thermal losses from the kiln surface without paint,

$$Q_{total} = Q_{conv} + Q_{rad}$$

While the actual kiln surface emissivity is to be measured, the value of 0.9 is believed to be an appropriate estimation based on different references for dark brown oxidized metal surface [4, 5]. The average gas temperature inside the kiln has been considered at 1050^0C and which produces a surface temperature of around 333^0C at emissivity of 0.9. The radiative flux (6474.26 W/m^2) is around 3 times the convective flux (1989.123 W/m^2). The Fig 8 shows the variation of different flux with respect to outer surface temperature at two different emissivities. The effect of radiative heat flux is more prominent than convective flux. Fig 8 shows that there is nearly a linear relationship of total heat flux with surface temperature at different emissivities. This sensitivity study allows us to obtain a range of the possible results due to variations of the parametric values and the assumptions made. It is observed that with lower emissivity the thermal losses are less and decreases with outer surface temperature.

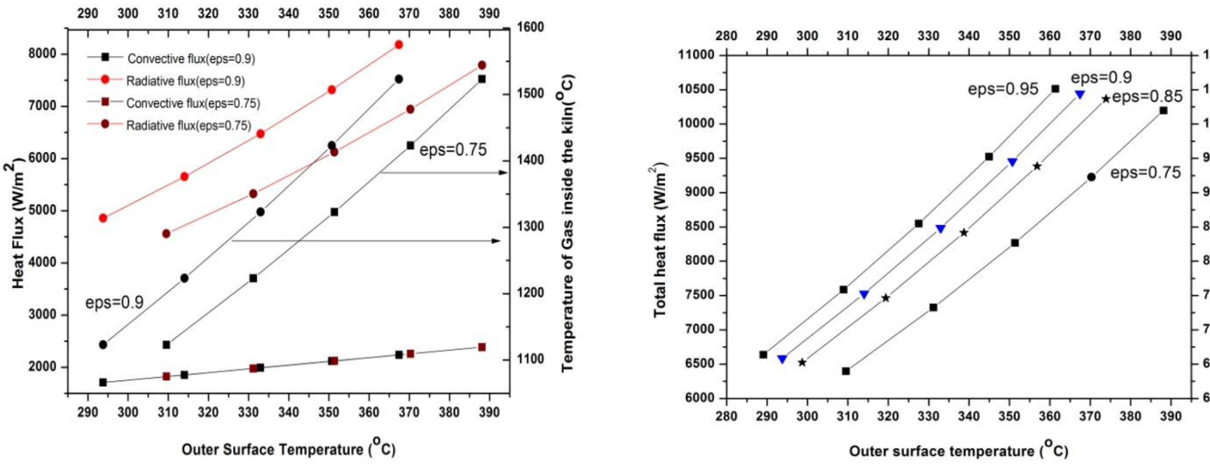

Fig 8 :Variation of heat flux with outer surface temperature (°C)

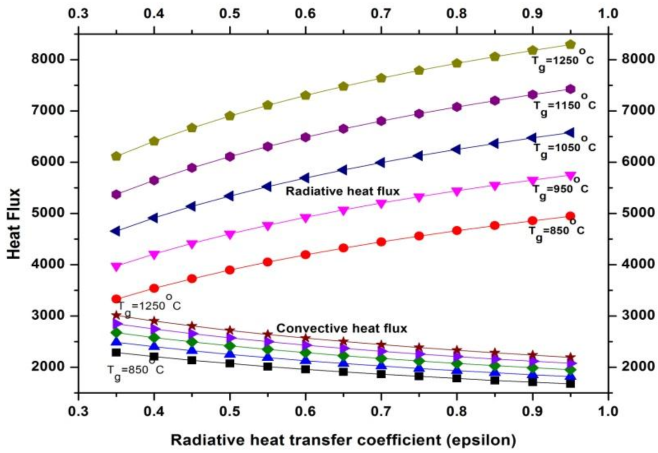

Fig 9 : Variation of heat flux with emissivity

To test the emissivity of the paint, a patch of the kiln surface close to the coke feed end was painted. Fig 10 shows the IR image of the surface without paint. The painted surface shows a slightly higher temperature and the emissivity obtained is 0.65. Thermal losses with paint are calculated and compared with those without paint. The paint layer is very thin, and its thickness can be ignored. The paint is assumed to cover the entire kiln surface. If only part of the kiln is to be painted, the energy savings will be roughly proportional to the painted area.

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Fig 9 shows that as the emissivity decreases due to application of paint, the radiative flux decreases but the convective flux increases and the total flux decreases. Fig 11 shows that though the total flux decreases but the corresponding outer surface temperature increases. For 1050^{0}C, it is observed that the total heat flux curve meets the surface temperature line at emissivity of 0.55 which can give the optimum results. Inside the kiln there is presence of turbulent flow which can be observed in fig 13 and the temperature drop along the radial length of rotary kiln can be seen in fig 12. In both Fig 12 and 13, the mid portion of the kiln is represented showing the temperature plot and flow inside the kiln.

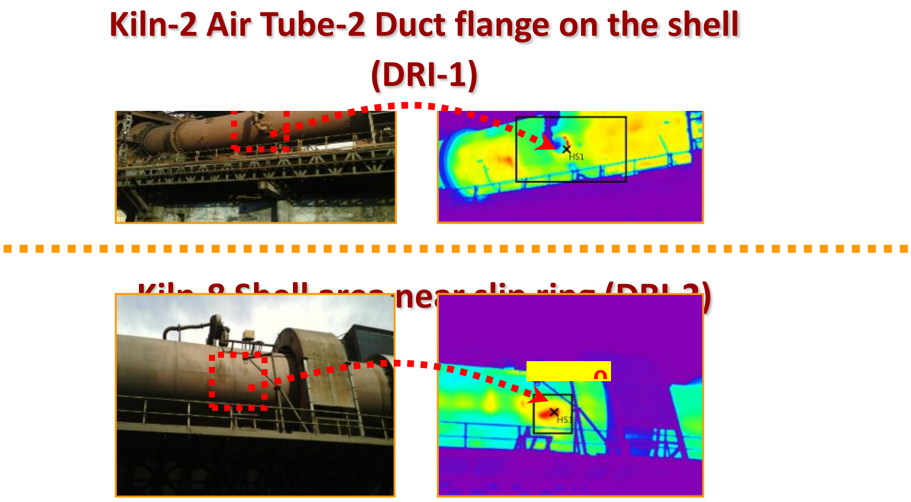

Fig 10: Rotary kiln and the IR image showing the surface temperature at DRI Plant

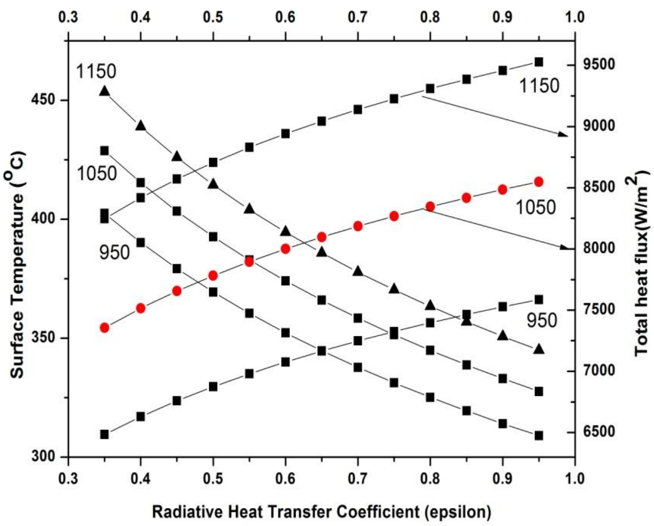

Fig 11: Variation of surface temperature and total heat flux with emissivity

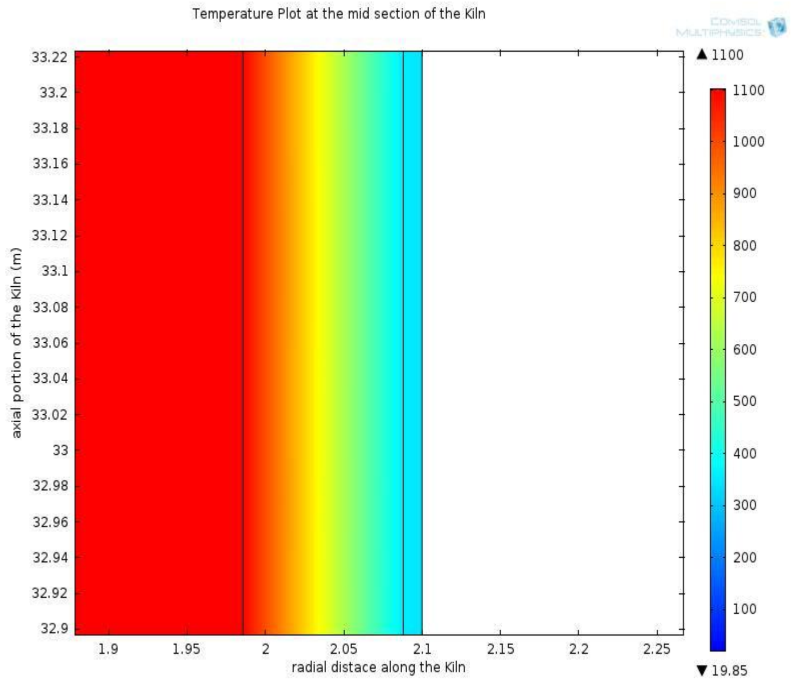

Fig 12: Temperature Plot along the radial length of the Kiln around mid portion of the Kiln

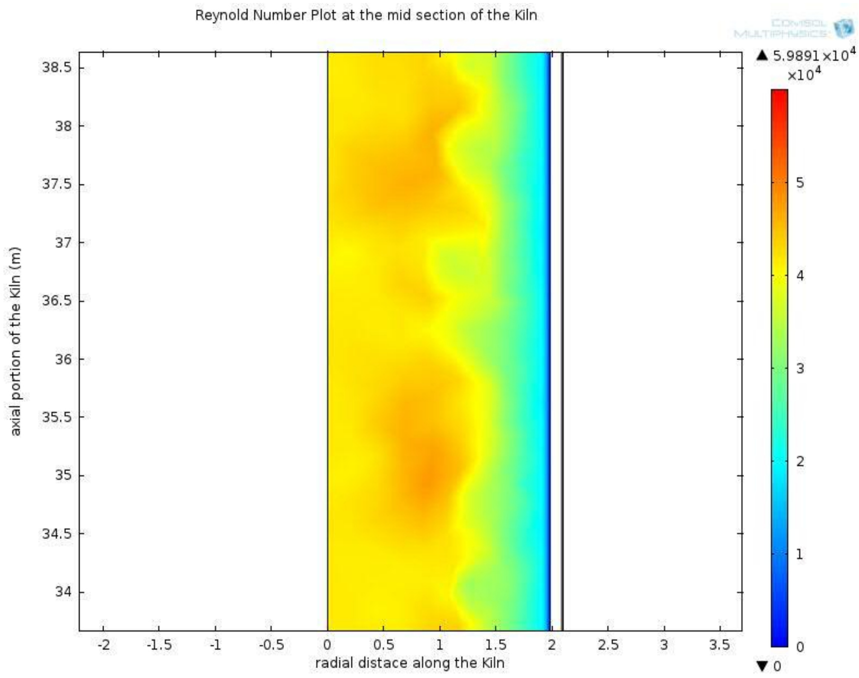

Fig 13: Reynold Number Plot along the radial length of the Kiln around mid portion of the Kiln

For the initial calculation, the gas temperature is assumed at 1050^{o}C and the outer surface temperature predicted by the simulation without paint is 334^{o}C. The result shows that the surface temperature with paint is around 366^{o}C and around 369kW of energy can be saved by reducing the thermal losses. The paint emissivity is taken as 0.65 and the simulation has been carried out for other two temperatures and the results have been shown in Table-II. The calorific value of coal has been obtained by using the properties as mentioned in Table-I and the necessary Calorific value of coal is obtained as 4600 Kcal/kg.

TABLE-II Properties of Coal

S.No	Properties	Value
1	Fixed carbon	37%
2	Volatile matter	32%
3	Ash	31%

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Table-III- Energy Saving by using paint at emissivity=0.65

Kiln Surface	Surface emissivity	T_{gas}	Total Heat Loss (W)	Surface Temp. (ºC)	Reduction in Heat Loss (kW) = (Total Heat Loss)$_{without\ paint}$ - (Total Heat Loss)$_{with\ paint}$	Energy Saving (kJ/day) = Reduction in Heat Loss (kW) * 60 * 60 *24	Per day Saving of Coal (kg/day) = Energy Saving (J/day)/ Calorific value of coal (Joule)	Increase in surface Temperature
Without Paint	0.9	1050	8060947	332.95	368.9	3,18,68,899	1649.5	32.95
With Paint	0.65		7692094	365.9				
Without Paint	0.9	1150	8984822	350.71	393.1	3,39,62,198	1757.9	35.09
With Paint	0.65		8591741	385.8				
Without Paint	0.9	1250	9920232	367.44	415.8	3,59,23,046	1859.4	37.12
With Paint	0.65		9504456	404.56				

The energy savings as well as the surface temperature increase are calculated for different gas temperatures possible inside the kiln. The sensitivity of the energy savings to the paint emissivity is also studied. Fig 14 shows the surface temperature increases with the decrease in paint emissivity. It has been observed that the energy savings increases when the paint emissivity decreases. However, the lower emissivity paint increase the kiln surface temperature by about 65ºC when paint with an emissivity of 0.5 is used. Based on the previous experiences from other plants, the surface temperature increase should be kept lower than 60ºC to avoid structural problems. Considering this temperature limit, the paint emissivity higher than 0.5 is acceptable for analysis. This can be well observed from Fig 14 and Fig 15 that with emissivity in the range of 0.55 to 0.65 will represent the better results in energy saving and structural problems can also be avoided. At emissivity of 0.3 though the coal saving is more but the increase in surface temperature can bring about the improper heating in the kiln.

TABLE-IV- Energy Saving by Using Paint At Emissivity=0.5

Kiln Surface	Surface emissivity	T_{gas}	Total Heat Loss (W)	Surface Temp. (ºC)	Reduction in Heat Loss (kW) = (Total Heat Loss)$_{without\ paint}$ - (Total Heat Loss)$_{with\ paint}$	Energy Saving (kJ/day) = Reduction in Heat Loss (kW) * 60 * 60 *24	Per day Saving of Coal (kg/day) = Energy Saving (J/day)/ Calorific value of coal (Joule)	Increase in Temperature
Without Paint	0.9	1050	8060947	332.95	668.2	5,77,31,918	2988.2	59.69
With Paint	0.5		7392753.5	392.64				
Without Paint	0.9	1150	8984822	350.71	713.9	6,16,78,022	3192.4	63.79
With Paint	0.5		8270956	414.5				
Without Paint	0.9	1250	9920232	367.44	756.7	6,53,79,398	3384.0	67.56
With Paint	0.5		9163526	435				

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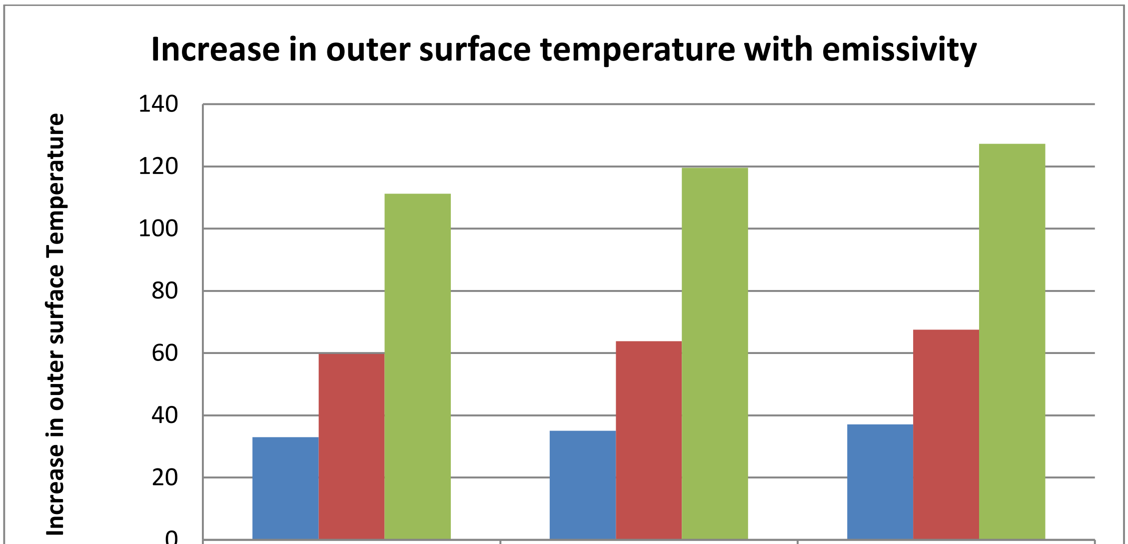
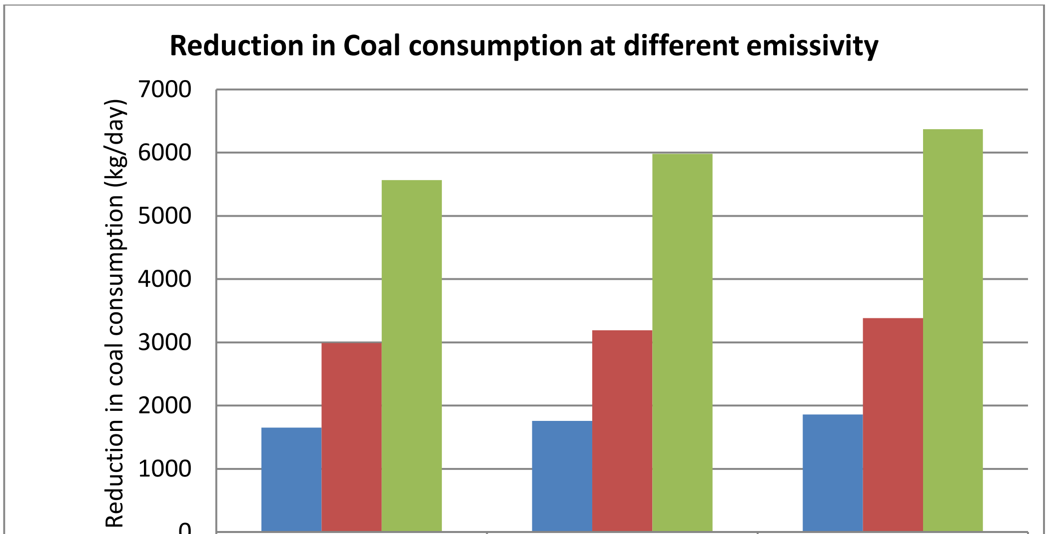


	1050 degC	1150 degC	1250 degC
0.9 to 0.65	32.95	35.09	37.12
0.9 to 0.5	59.69	63.79	67.56
0.9 to 0.3	111.25	119.49	127.26

Fig 14: Increase in outer surface temperature with application of paint



	1050 degC	1150 degC	1250 degC
0.9 to 0.65	1649.5	1757.9	1859.4
0.9 to 0.5	2988.2	3192.4	3384
0.9 to 0.3	5567.2	5981.5	6371.5

Fig 15: Reduction in coal consumption with the application of paint

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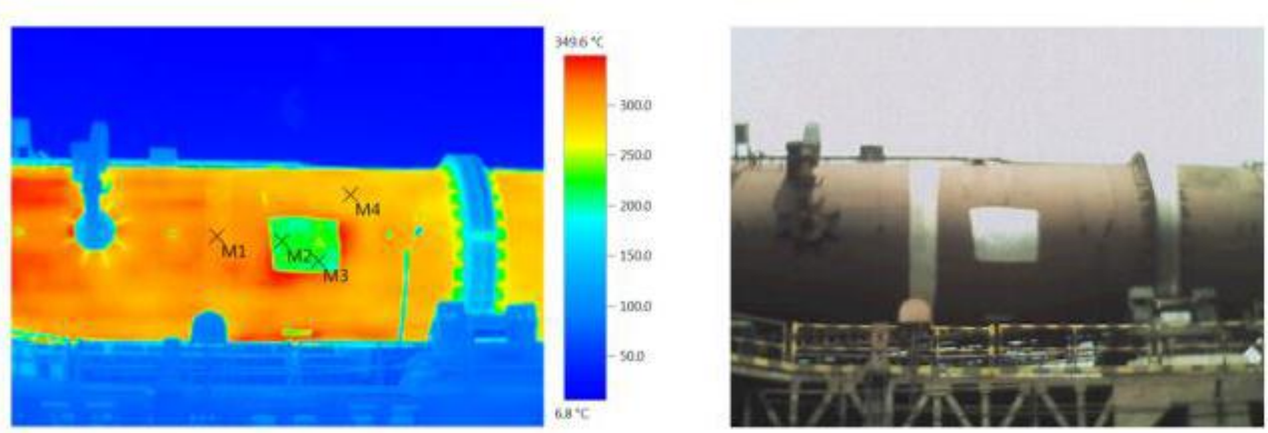
Table-V- Energy Saving by using paint at emissivity=0.3

Kiln Surface	Surface emissivity	T_{gas}	Total Heat Loss (W)	Surface Temp. (°C)	Reduction in Heat Loss (kW) = (Total Heat Loss)$_{without\ paint}$ - (Total Heat Loss)$_{with\ paint}$	Energy Saving (kJ/day) = Reduction in Heat Loss (kW) * 60 * 60 *24	Per day Saving of Coal (kg/day) = Energy Saving (J/day)/ Calorific value of coal (Joule)	Increase in Temperature
Without Paint	0.9	1050	8060947	332.95	1244.9	10,75,57,891	5567.2	111.25
With Paint	0.3		6816064	444.2				
Without Paint	0.9	1150	8984822	350.71	1337.5	11,55,62,678	5981.5	119.49
With Paint	0.3		7647291	470.2				
Without Paint	0.9	1250	9920232	367.44	1424.7	12,30,97,795	6371.5	127.26
With Paint	0.3		8495489	494.7				



Picture parameters:
Emissivity: 0.70
Refl. temp. [°C]: 20.0

Picture markings:

Measurement Objects	Temp. [°C]	Emiss.	Refl. temp. [°C]	Remarks
Measure point 1	316.6	0.70	20.0	-
Measure point 2	225.2	0.70	20.0	-
Measure point 3	216.4	0.70	20.0	-
Measure point 4	292.2	0.70	20.0	-

V. CONCLUSIONS

1 Based on a kiln surface emissivity of 0.9 and an average temperature of gas at 1050°C, the surface temperature is around 332°C. The thermal loss of natural convection and radiation from the kiln surface is about 8060.94 kW.

2 A sensitivity study shows that the thermal losses depend largely on the surface temperature.

3 Painting the surface using paint with an emissivity of 0.5 reduces the thermal losses to 7392.75 kW which means an energy saving of 668.2 kW. The surface temperature will increase by 59 °C. The natural convection will increase, but the radiation loss well decrease. The net effect is a reduction in thermal losses.

4 The paint emissivity has a significant effect on the kiln surface heat transfer. Lower emissivity paint decreases thermal losses but increases the kiln surface temperature. For example, using paint with an emissivity of 0.3 leads to an increase of 90-110 °C in the kiln surface temperature. A large increase of the kiln surface temperature is not ideal because it will cause structure problems induced by large differential thermal expansion between the metal shell and the bricklayer. Therefore, the proposed paint with an emissivity of 0.5 to 0.65 is appropriate.

5 The reduction in coal consumption (kg/day) by applying paint of emissivity 0.5 on kiln surface is approximately 3000 kg/day.

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