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Heat Transfer Analysis of Blast Furnace Refractory Lining

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This paper gives a systematic study of blast furnace cooling stave with refractory lining materials used in the metallurgical industries based on heat transfer analysis. The three dimensional model of heat transfer of cooling stave with refractory lining in a blast furnace are modelled and analyzed with the help of ANSYS software. The model further utilized for the heat transfer analysis of different thickness of lining materials. The Refractory lining material which is used in this experiment are mullite bricks (65%Al2O3&35%SiO2) with different stave materials (copper, aluminium and cast iron). We have identified a stave cooler in RSP (Rourkela steel plant) blast furnace -4 in Bosh zone where heat load is maximum for our experiment purpose. The data collected from RSP is used for developing a 3 D model of heat transfer analysis of refractory lining with stave cooling. We collected the heat flux data of subjected stave cooler and tabulated for our experimental study. The experiment result collaborates with the actual result developed in the 3D model. Further, In this study refractory lining thickness of the blast furnace is taken as 650mm from the inner side of the furnace to the stave body by gradually decreasing the refractory lining thickness up to 550mm. Copper and aluminum is used in place of cast iron as stave material, the factor of safety of the stave material is greatly enhanced due to higher thermal conductivity.

Keywords*: *Blast Furnace, Heat transfer, Refractory linings, Cooling stave.

Introduction

In consideration of the vast capital investment required for blast furnace relining, great efforts have been made to extend the campaign life of blast furnaces. Lining is the most important factor for determining the campaign life of a blast furnace. The cooling of refractory lining is the most contributing factor in deciding the Furnace campaign life. Lining cooling by stave technology is one of the products of such efforts. A stave is a cooling device having one or more internal channel, and is installed in numbers on the inner surface of a blast furnace to protect its steel shell and maintain the inner profile. The staves were made conventionally of cast iron. But now days copper staves are used in place of cast iron staves, which is excellent in heat conductivity. Water is used as a medium for transfer of excess heat from inside the furnace to keep the lining cooled & prevent it from faster wearing out. Figure 1 indicates arrangement of stave cooler in a blast furnace for lining cooling.

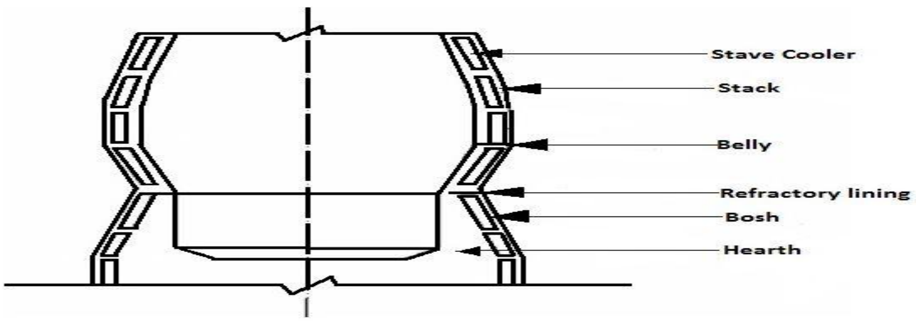


Figure 1.1 Arrangement of stave coolers in a Blast Furnace

Experimental Analysis

This work is about the three dimensional modelling and numerical analysis of the actual stave coolers with refractory lining used in blast furnace of Rourkela Steel Plant. we have identified a stave cooler for experimental base which is subject to maximum heat load in the furnace. A analytical model has been developed the with the help of ANSYS software taking actual dimension from RSP data base. To develop the model we have design the dimensionally identical cooling coil with the help of work bench. The cooling coil developed is super imposed in a rectangular box dimensionally identical to the subjected experimental stave cooler. The model developed is exactly dimensionally identical to the actual stave cooler used in RSP .The model developed with the help of work bench is export to fluent to study the theoretical heat transfer behaviour of stave cooler vis a vis the actual heat load in the furnace.

We take the practical data from the experimental set up based on the same identified stave cooler of the blast furnace.

The experimental base is consisting of two numbers of temperature measuring devices fitted to the inlet and outlet of subjected stave cooler. Volume flow meter is installed in the inlet line to measure the volume flow inside to the stave cooler. A pressure gauge is installed in the fluid flow line to indicate the fluid pressure in the subject stave cooler.

From the experimental set up we measure the actual heat load in subject stave cooler table given below; we noted the inlet and outlet temperature and difference of temperature there off in the stave cooler (dT) in a particular volume of fluid flow.

When the same heat load calculated from experimental set up is put in analytical model. The temperature difference (dT) found to be as in the actual set up. The above experimental is continued for different types of fluid in our setup. We have measured the experimental setup value using water as cooling medium and then we replace it with nitrogen. The value obtained practically found to be exactly identical as in the software model. The experimental setup as shown in the Figure 3.1

Figure 3.1 Experimental setup

Experimental Data

These are some experimental data taken from Rourkela steel plant using water as a cooling agent given below in Table 3.1.

Table 3.1 Experimental Data

Stave cooler	Inlet temp(T_1) in ^oC	Outlet temp(T_2) in ^oC	Difference ($T=T_2-T_1$)	Water collected (litres)	Time in second	Volume (m3/hr)	Heat extract (kcal/hr)
1	27.4	32.8	5.4	30	54	2.00	10800.00
2	27.4	30.8	3.4	30	64	1.69	5737.50
3	24.4	30.8	6.4	30	60	1.80	11520.00
4	24.4	35.6	11.2	30	48	2.25	25200.00
5	24.4	33.2	8.8	30	46	2.35	20660.87
6	24.4	31.4	7	30	43	2.51	17581.40

7	24.4	32.8	8.4	30	57	1.89	15915.79
8	24.4	35.4	11	30	44	2.45	27000.00
9	24.4	34	9.6	30	47	2.30	22059.57
10	24.4	32.6	8.2	30	43	2.51	20595.35
11	24.4	31.6	7.2	30	52	2.08	14953.85
12	24.4	30.6	6.2	30	54	2.00	12400.00
13	24.4	32.8	8.4	30	48	2.25	18900.00
14	24.4	37.6	13.2	30	53	2.04	26898.11
15	24.4	30.2	5.8	30	48	2.25	13050.00
16	22.4	30.4	8	30	51	2.12	16941.18
17	22.4	30.4	8	30	48	2.25	18000.00
18	22.4	28.4	6	30	53	2.04	12226.42
19	22.4	28.2	5.8	30	58	1.86	10800.00
20	22.4	27.8	5.4	30	54	2.00	10800.00
21	22.4	29	6.6	30	55	1.96	12960.00
22	22.4	30.2	7.8	30	58	1.86	14524.14
23	22.4	30.2	7.8	30	59	1.83	14277.97
24	22.4	27.2	4.8	30	51	2.12	10164.71
25	22.4	32.8	10.4	30	53	2.04	21192.45
26	22.4	33.4	11	30	47	2.30	25276.60
27	22.4	35.4	13	30	54	2.00	26000.00
28	27.4	37.4	10	30	53	2.04	20377.36
29	27.4	31.4	4	30	48	2.25	9000.00
30	27.4	32.2	4.8	30	52	2.08	9969.23
31	27.4	33.2	5.8	30	47	2.30	13327.66
32	27.4	34.2	6.8	30	69	1.57	10643.48
33	27.4	37.2	9.8	30	46	2.35	23008.70
34	27.4	31.2	3.8	30	58	1.86	7075.85
35	27.4	30.6	3.2	30	53	2.04	6520.75
36	27.4	30.6	3.2	30	52	2.08	6648.15
37	27.4	32.4	6	30	55	1.96	9818.18
38	27.4	29.6	2.2	30	58	1.86	4096.55

Numerical Analysis

In Present study model of blast furnace refractory lining with cooling is done by the help of software ANSYS. In this software workbench is specially used for geometry and meshing of the model. There are some steps explain below:

Geometric Modelling: A three dimensional refractory lining with stave cooling having original dimension of 1640 mm length, 898mm height and 850mm width is drawn by the help of design modular. First of all I have drawn coil of the stave having dimension of 33mm diameter and 8421mm total length and the bending radius of the coil is 80mm as shown in the Figure 3.1 respectively .After completion of the coil I have drawn the stave body with coil of 1640mm length,898mm height and 200mm width as shown in the Figure 3.2, Further it was extruded by 650mm in z-direction for addition of lining material as shown in the Figure 3.3 and figure 3.4 showing meshing of stave cooler with refractory lining respectively.

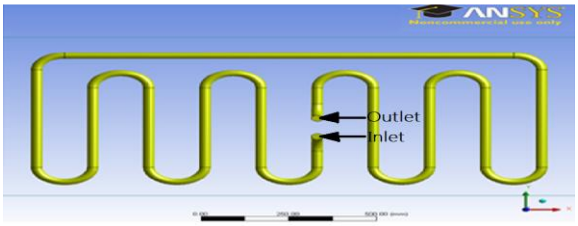


Figure 3.1 Stave coil in x-y coordinates

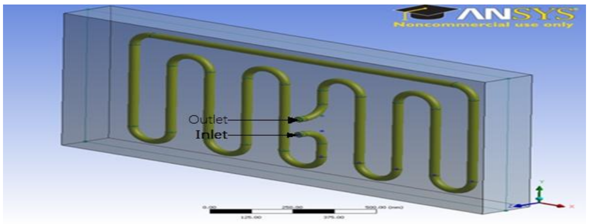


Figure 3.2 Isometric view of stave cooler

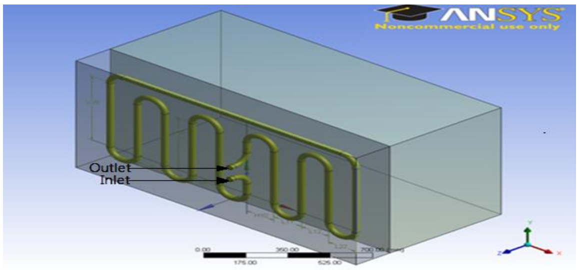


Figure 3.3 Isometric view of stave cooler with refractory lining

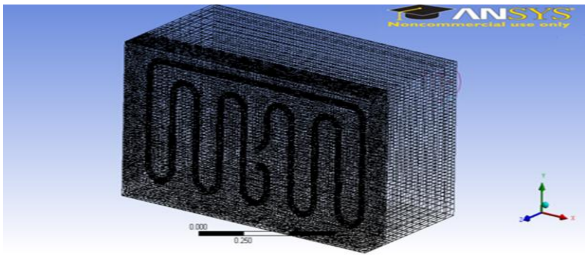


Figure 3.4 meshing of stave cooler with refractory lining

Basic Equation Of Fluid Flow

1. Continuity Equation:

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \qquad (1)$$

2. Navier-Stokes Equation:

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=\rho x-\frac{\partial p}{\partial x}+\frac{1}{3}\mu\frac{\partial}{\partial x}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)+\mu\nabla^2 u \qquad (2)$$

3.EnergyEquation: (3)

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)=\left(u\frac{\partial p}{\partial x}+v\frac{\partial p}{\partial y}+w\frac{\partial p}{\partial z}\right)+k\nabla^2 T+\mu\phi$$

Where, $\phi=2\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial w}{\partial z}\right)^2\right]+\left[\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2+\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)^2+\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)^2\right]-\frac{2}{3}\left[\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right]^2$

Heat extracted Q (Kcal/hr) $Q=m\times C_p\times dT$

Where, m = Weight of the water in kg

Cp= specific heat of water in kcal/kg^{0}C

T_2 = outlet temperature of water in ^{0}C

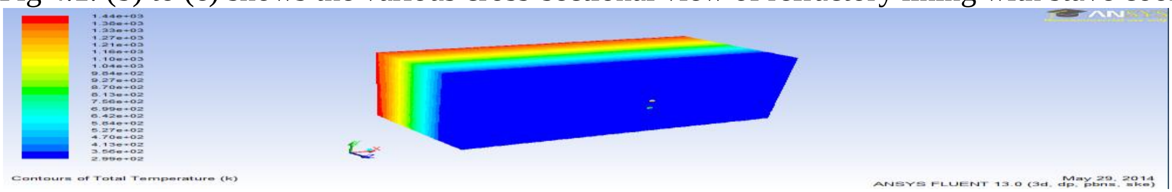
T_1 = Inlet temperature of the water before it enters the furnace in ^{0}C

Results and Discussion

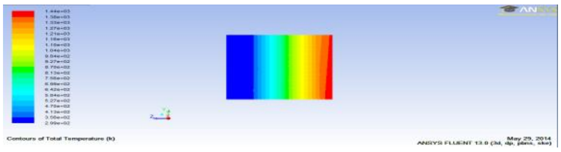
The numerical analysis has been done for the refractory lining with stave cooler by choosing both water and nitrogen as a cooling agent and have compared the temperature difference generated at the inlet and outlet of stave cooler.

Numerical analysis of staves with refractory lining contour has been shown in Figure 4.1(a). It shows the variation of temperature across the surface of the stave material with refractory lining for thickness of 650mm. The heat wall (innermost surface of the refractory lining) shows the highest temperature of 1440 K. This is because heat flux is directly applied to this surface. With increase in distance in a direction away from the heat wall, the temperature gradually decreases. At the interface of the refractory lining and the stave material temperature was found to be 397 K. Inlet temperature of the cooling fluid was 300 K and at outlet its temperature was found to be 307.8K, which shows 7.8 K rise in temperature.

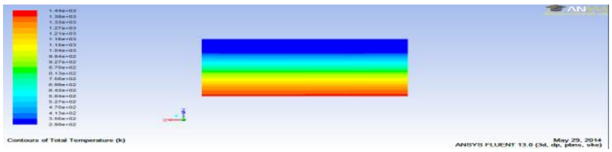
Fig 4.1. (b) to (e) shows the various cross-sectional view of refractory lining with stave cooler.



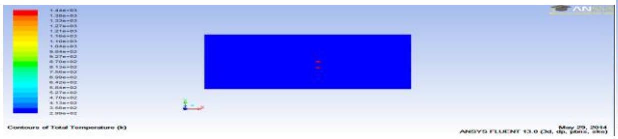
((a)



(b)



(c)



(d)

(e)

Figure 4.1 3D model of refractory lining (650mm) with stave cooler (a) Isometric view (b) Side view (c) Top view (d) Front view (e) Rear view.

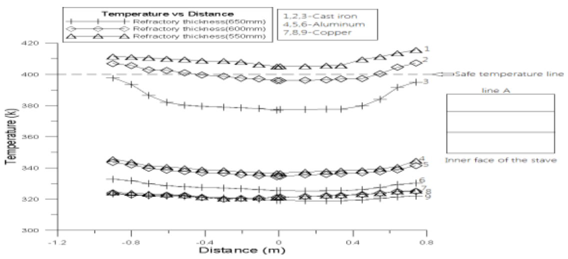


Fig.4.4

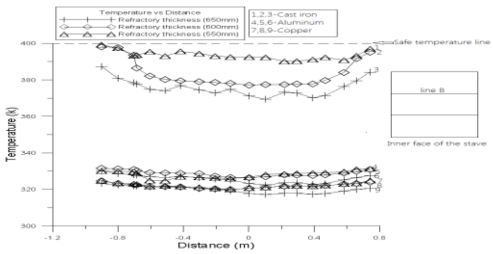


Fig.4.5

Figure 4.4 Temperature variations with distance for different refractory thickness with different stave materials at inner face of the stave **(line A)**

In this graph 4.4, we have analyzed the inner face of stave at line A by taking different stave material at different thickness of refractory material. When we take refractory thickness of 650mm having cast iron as a stave material temperature variation is found below the safe temperature limit, which is desirable. With decrease in thickness of the refractory material the temperature variation curve was found to increase. It also crosses the safe temperature limit, hence it is not desirable. At

600mm it was found fluctuating between safe and unsafe limit, and at 550mm thickness it was completely above the safe limit.

It can be seen in the curve that with increase in distance from the canter temperature remains constant for some time and then gradually increases at larger distance. It happens because cooling coil is present at the canter; hence more cooling occurs at the canter, but at the corner because distance is more, so cooling is less.

Similar pattern was also observed for aluminium and copper as a stave material but all below the safe temperature limit. Among the three materials copper was found to be the best material as compared to cast iron and aluminium. It is because very large amount of heat is dissipated by copper as compared to others.

We have also seen that as cast iron is very close to the safe limit, any reduction in thickness due to high heat generation causes severe damage.

Figure 4.5 Temperature variations with distance for different refractory with different stave materials at inner face of the stave **(line B)**

In this graph 4.5, also we have analyzed the inner face of stave at line B by taking different stave material at different thickness of refractory material. In this case we found that temperature variation curve was always below the safe limit at any refractory thickness ranging from 550mm to 650mm. Here also we found the same pattern as line A .It was also observed that for aluminium and copper cooling effect is uniform throughout the stave.

For Aluminium and copper as a stave material, the temperature generation is found to be lesser than the safe limit because of more thermal conductivity of respective materials which releases the heat faster. We can observe from the graph that the thickness variation of refractory doesn’t affect much in the temperature generation. So we conclude that it can sustain for long period of time because of less affect of thickness of refractory on temperature generation.

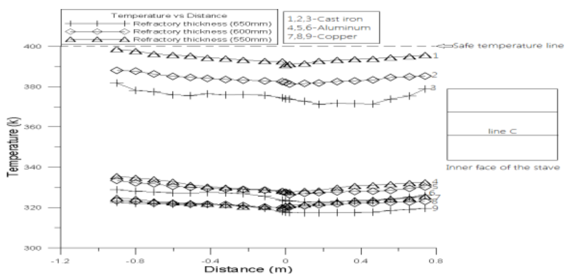


Fig. 4.6

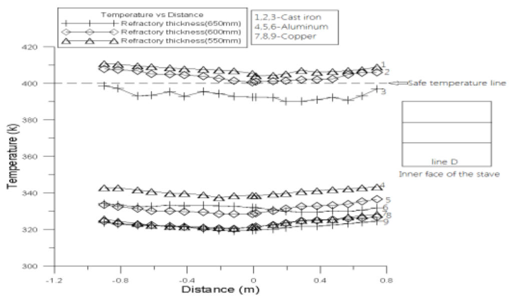


Fig. 4.7

Figure 4.6 Temperature variations with distance for different refractory thickness with different stave materials at inner face of the stave **(line C)**

In this graph 4.6, we have analyzed the inner face of stave at line C by taking cast iron, aluminium and copper as stave material at different thickness of refractory material. In this case we found that temperature variation curve was always below the safe limit at any refractory thickness ranging from 550mm to 650mm.

For cast iron temperature variation curve was always below the safe limit because line C is near the centre of the stave and close to cooling coil, hence heat is dissipated quickly. All other patterns remain the same. With decrease in refractory thickness the temperature increases. But as cast iron thermal conductivity is less it is very close to the safe temperature limit, hence not very suitable for use.

For Aluminium and copper as a stave material, the temperature generation is found to be lesser than the safe limit because of more thermal conductivity of respective materials which releases the heat faster. We can observe from the graph that the thickness variation of refractory doesn’t affect much in the temperature generation. So we conclude that it can sustain for long period of time because of less affect of thickness of refractory on temperature generation.

Figure 4.7 Temperature variations with distance for different refractory thickness with different stave materials at inner face of the stave **(line D)**

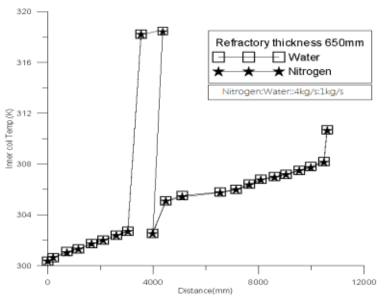
Similar pattern was also observed in case of line D. But as line D is far from the cooling coil heat dissipation is less. Hence we find that when refractory thickness is either 550mm or 600mm for cast iron temperature generated is above safe limit, which was not in the case of line C. But at 650mm it was found to be below safe limit due to large refractory thickness.

For aluminium and copper as usual their temperature variation is found below the safe temperature limit. Copper due to its higher thermal conductivity is more preferred material, because it was seen that temperature generated is least among all three materials.

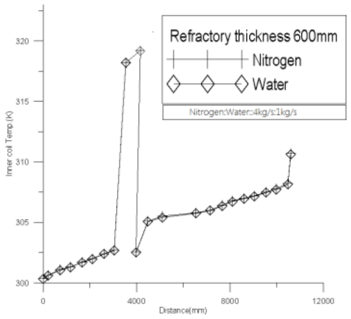
Fig.4.8 shows the variation of temperature with increase in length of the coil when nitrogen and water is used as cooling agent for refractory thickness of 650mm. It was observed that same curve can be obtained if we increase the mass flow rate of nitrogen by four times as that of water, then same cooling effect can be obtained.

Here we see that with the increase in length, temperature increases slowly, while approaching the extreme end of the stave heat increases gradually. But the rise in temperature is rapid when it reaches the extreme corner of stave- refractory interface. The temperature slumps down suddenly while approaching the outlet. However, the gradual rise is observed when the cooling agent reaches the outlet. Finally, the outlet temperature is little higher than the inlet temperature due to heat absorption in the entire process.

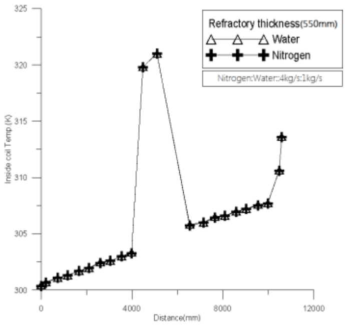
Same phenomenon was also observed when we simulated on the refractory having thickness of 600mm as shown in Fig.4.9 and also for refractory having thickness of 550mm as shown in Fig.4.10.



(Figure 4.8 Inner coil temperatures versus distance (Refractory thickness 650mm)



(Figure 4.9 Inner coil temperatures versus distance (Refractory thickness 600mm)



(Figure 4.10 Inner coil temperatures versus distance (Refractory thickness 550mm)

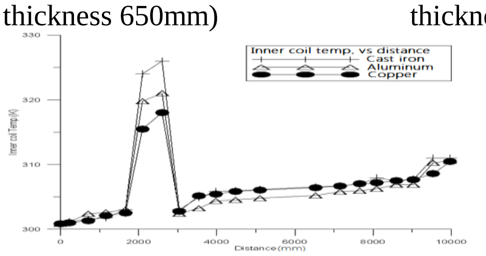


Figure 4.11 Inner coil temperatures versus distance

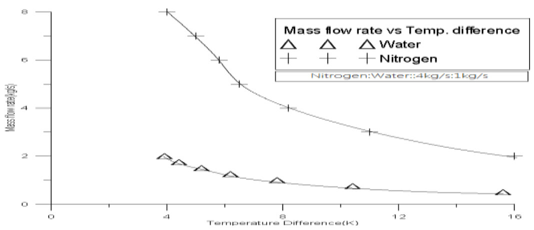


Figure 4.12 Mass flow rate versus Temperature difference

We have three materials viz. cast iron, aluminium, and copper are used as a stave materials. All the three are treated with water in order evaluate the temperature variations at a particular instant of length. The inlet temperature for all the three stave coils is given as 300 K. From the Fig.4.11; we observe that the outlet temperature for all the three stave coils is also equal. However, the Figure depicts a sudden rise at a particular point in all the three coils. We also observe that, the temperature rise is dominated in the case of copper coil followed by aluminium and cast iron coil respectively. This phenomenon is observed basically at the point nearer to the stave corner approaching the refractory lining.

The Fig.4.12; depicts the relationship between mass flow rate of water and nitrogen in the coil with respect to the temperature difference. The quantity of nitrogen is taken four times than that of the quantity of water in this experiment. However, we observe that the temperature difference for both the cooling agents (water and nitrogen) varies in the similar manner.

Conclusions

In present research work experimental and numerical analysis has been done for the refractory lining with stave cooler. Experimental result almost matched with numerical result. From the obtained results it can be concluded that:

1. If copper and aluminum is used in place of cast iron as stave material, the factor of safety of the stave material is greatly enhanced due to higher thermal conductuctivity. As a result, the stave will sustain for longer period i.e relining period of the refractory is increased. Also production is increased and the cost for relining and manpower is reduced significantly.
2. The temperature variation from the inner part of refractory lining to the inteface of stave-rafractory decreases linearly with respect to the instantaneous length.
3. By using the mass flow rate of nitrogen as four times than that of water, we get the desirable results as compared to water due to abundance of nitrogen in the industrial wastage.

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