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Experimental and Numerical Analysis of Blast Furnace Cooling Stave with Refractory Lining

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In this present systematic review and study of Blast furnace cooling stave with the refractory lining materials used in the metallurgical industry based on heat transfer analysis. The three dimensional stave cooler with Refractory linings of a blast furnace are model and analyzed with the help of ANSYS software. Further three dimensional model utilized for the heat transfer analysis of different thickness of Refractory lining material. The Mullite bricks (65% of Al2O3 and 35%of SiO2) have been used as a Refractory Lining material for this Experiment with different stave cooler materials (Cast iron, copper and aluminium). Stave cooler have identified in Rourkela steel plant (blast furnace #4) in Bosh zone, In this zone maximum heat load is obtained. The Experimental data collected from Rourkela steel Plant is used for developing 3D model of heat transfer analysis of subjected stave cooler with refractory lining. The Actual result collaborates with the Experimental result which developed in the 3D model. Further, In this study, blast furnace refractory lining thickness is taken as 0.65m from the inner side of the furnace to the stave body by gradually reducing the refractory lining thickness up to 0.55m. Aluminium and Copper both materials would be used in place of cast iron as stave material, the factor of safety of the stave cooler is gradually enhanced due to the higher thermal conductivity and also Nitrogen to be used in place of water as a cooling agent.

Keywords**:** *Blast Furnace, Heat transfer, Refractory lining, Interface, stave Cooler.*

Introduction

A Blast Furnace (BF) is a metallurgical device used for smelting the iron ore, generally produce steel after several processes, in a BF, iron ore coke and limestone are continuously supplied on the top of the furnace, which is upper hopper and lower hopper. while hot blast is blown into the furnace through tuyere, there are number of tuyere arranged on the hearth of the furnace so that the combustion take place inside the furnace from the bottom to top as the material moves. Molten metal collected from tap hole and from the slag hole slag are getting out. Flue gases or exhaust gases out top of the furnace.

For relining period of the BF would be define the campaign life of the furnace and also cooling of the refractory lining (RL) material be the most contributing factor of the furnace life. stave technology is the one of the best product of such efforts, The stave cooler(SC) is consists of one or more than one internal channel which is installed between outer surface of the RL and inner side of the steel shell to protect both of it, usually maintained the inner profile. The stave cooler was prepared usually on cast iron. But present days instead of cast iron we have used copper, which is transfer more heat than that of other due to its greater conductivity of heat. Cooling Water being used to transfer more heat from the lining of the furnace and also it protect faster wearing out. Fig. 1.1 Arrangement of SC and RL in the Furnace

Cheng-Peng Yeh et al. [1] studied the heat transfer (HT) of different RL thickness with the aluminium staves and a sensor bars. *Gdula et al.* [2] explained on transfer of heat of BF hearth which is on the (lower zone) was based on non identical cooling system and RL material had measured.

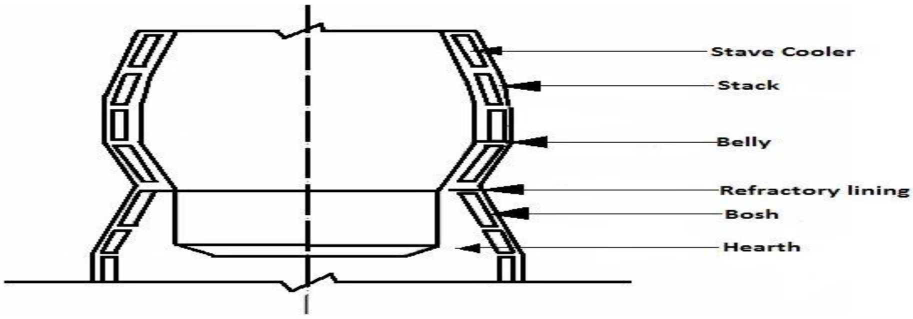


Fig. 1.1 Arrangement of SC and RL in the Furnace

Chang et al. [3] found the BF hearth zone of the erosion formation during tapping process. *Y. Kaymak.* [4] Maintained the Thermo-mechanical contact of stave and RL. *Maria Swartling.* [5] He analyzed on the flow of Heat in the BF Hearth zone. *Cheng Hui'er et al.* [6] he explained about the cast steel stave cooling rectangular channel in the furnace. *Anil Kumar et al.* [7] considered on computational cooling stave model of BF which is based on transfer of heat,

Different materials used in BF:

Table 1.1 These materials has been used in the three dimensional mathematical modelling for the HT analysis of furnace RL with SC .

Table 1.1

Typesof fluids/materials	Specific heat in (KJ/KgK)	ThermalConductivity (W/mK)	Density of the material (Kg/m3)
Water	4.187	0.6	998.2
Nitrogen	1.040	25.83X 10^{-3}	1.251
Stave materials			
Cast iron	0.460	40	7500
Aluminium	0.871	202.4	2719
Copper	0.381	385	8978
Refractory materials			
Al_2O_3	0.880	18	3690
SiO_2	0.700	1.4	2648
Mullite	0.760	12	2950

Experimental Analysis of SC with RL:

In this present experimental and numerical analysis of particular SC in BF #4 in the Rourkela steel plant. One SC has been identified on the bosh zone of Furnace for the experimental purpose; this zone is marked to be maximum heat load in the furnace. Actual data of the particular SC has taken from RSP data centre. We have taken the actual data from the identified SC in the BF. The temperature measuring device is fitted in the inlet and outlet of the identified SC to measure the inlet and outlet temperature of the stave .we have installed a Volume flow meter on the inlet of the SC to measure the flow rate and A pressure gauge has install in fluid flow coil to point out the fluid pressure .

From the Particular setup we have measured and collected the data of heat extraction , inlet and outlet temperature ,volume flow rate of the water ;which is given on the below table 3.1. And the above experiment was being carried out for another fluid in the same setup, initially we had taken water as a fluid for cooling purpose and then nitrogen being replaced by water for the cooling of RL. The experimental setup of the RSP as shown in the Figure 1.2

Fig. 1.2 Blast Furnace #4 Experimental setup

Experimental Data of the Subjected SC:

Experimental data has been taken from RSP (BF #4), Table 3.1.shows the data using water as a cooling agent and Table 3.2 shows the data using nitrogen as a cooling agent

Table 3.1 Experimental Data using water (cooling agent)

Stave cooler (#)	Inlet temp(T_1) in (^oC)	Outlet temp(T_2) in (^oC)	Difference of temp ($T=T_2-T_1$)	Water collected in litres	Time in (sec)	Volume flow in (m3/hr)	Heat extracted (kcal/hr)
1	27.4	32.8	5.4	30	54	2.02	10800.10
2	24.4	33.9	9.5	30	56	1.90	15925.69
3	24.4	34.2	9.8	30	44	2.44	26999.01
4	24.4	34.1	9.7	30	47	2.31	22059.56
5	24.4	32.6	8.2	30	43	2.52	20595.34
6	24.4	31.5	7.1	30	53	2.07	14953.84
7	24.4	30.6	6.2	30	54	2.01	12400.01
8	24.4	32.7	8.3	30	48	2.24	18900.01
9	24.4	37.6	13.2	30	53	2.03	26898.10
10	24.4	30.1	5.7	30	47	2.24	13050.01
11	22.4	30.4	8	30	51	2.11	16941.17
12	22.4	30.4	8	30	48	2.24	18000.00
13	22.4	28.4	6	30	53	2.03	12226.41
14	22.4	28.1	5.7	30	57	1.85	10800.02
15	22.4	27.8	5.4	30	54	2.01	10800.03
16	22.4	29.1	6.7	30	55	1.95	12960.04
17	22.4	30.2	7.8	30	57	1.85	14524.12
18	22.4	30.1	7.7	30	59	1.82	14277.96
19	22.4	27.2	4.8	30	51	2.11	10164.70
20	22.4	32.7	10.3	30	53	2.03	21192.44
21	22.4	33.4	11	30	47	2.31	25276.59
22	22.4	35.4	13	30	54	2.01	26000.01
23	27.4	37.5	10.1	30	53	2.03	20377.26
24	27.4	31.4	4	30	49	2.24	9000.01
25	27.4	32.1	4.7	30	52	2.07	9969.21
26	27.4	33.1	5.7	30	47	2.31	13327.65
27	27.4	34.1	6.7	30	68	1.56	10643.47
28	27.4	37.2	9.8	30	46	2.34	23008.69
29	27.4	31.1	3.7	30	58	1.85	7075.84
30	27.4	30.6	3.2	30	54	2.03	6520.65
31	27.4	30.5	3.1	30	52	2.07	6648.14

Table 3.2 Experimental data of nitrogen

S.N.#	Number of turns	Opening valve (%)	Inlet temperature (oC)	Outlet temperature (oC)
1	2	66.67	29	30.1
2	3	50	29	32.7
3	4	33.33	29	37.2
4	5	16.67	29	39.8
5	6	1	29	41.2

Numerical Analysis

In this present study and view the SCRL model of BF has been done using the ANSYS software, initially for geometry and mesh of the cooler we have been used specially workbench. There are few steps explain below:

Geometric Model of SCRL: The dimension of 3D stave cooler with refractory lining (SCRL) have been taken from RSP data centre, These data are the width of 0.85m , length of 1.640m and height of 0.898m ,diameter of the coil 0.033m and coil bending radius 0.08m drawn by the use of design modular . total length of the coil been taken as 8.421m as shown in the Figure 3.2 respectively .figure 3.3 show the stave body, which dimension are of 1.640m length,0.898m height with 0.2m width, Further it has extruded in the z-direction by 0.65m for adding together of RL material as shown in fig. 3.4 and the fig. 3.5 shown the meshing of SCRL respectively.

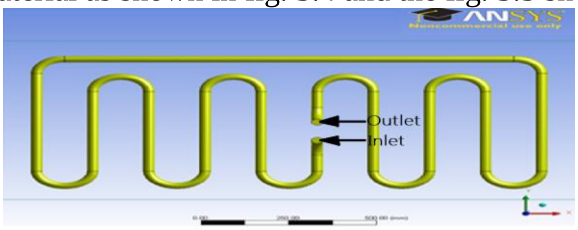


Fig. 3.2 Front view of SC coil

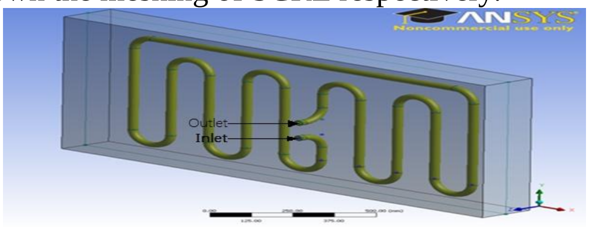


Fig. 3.3 Front view of SC

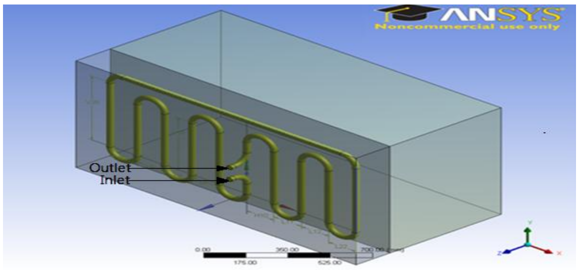


Fig. 3.4 Front view of SCRL

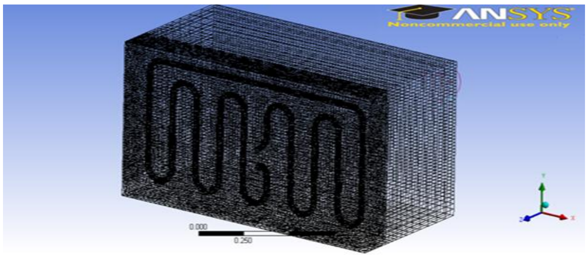


Fig. 3.5 Meshing of SCRL

Basic equation of fluid flow:

1. Continuity equation: (to apply the conservation of mass)

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

2. N-S equation: (to apply conservation of momentum)

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

3. Energyequation :(to apply conservation of energy) (3)

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

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

$$-\frac{2}{3}\left[\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right]^2$$

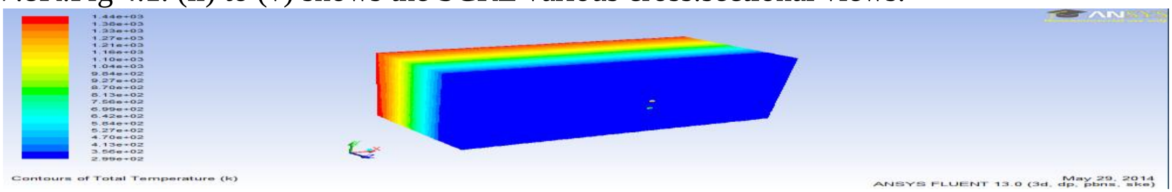
Heat extraction, Q (Kcal/hr), $Q = m \times C_p \times dT$

Whereas, $\dot{m}$ = mass flow rate of water, kg/s
C_p= specific heat of water, kcal/kg^{0}C
T_2 = outlet temperature of water, ^{0}C
T_1 = inlet/atm temperature of the cooling water, ^{0}C

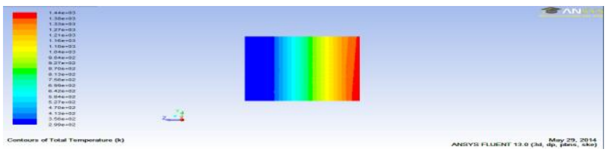
Results and Discussion

The 3D model of SCRL numerical analysis has done using different cooling agent like (water and nitrogen) and also inlet and outlet temperature difference of SC being compared. Figure 4.1(i) shown the contour of SCRL and it shows the temperature variation across the plane of 0.65m thickness. The inner surface of the heat wall (inside the furnace) shows the maximum temperature of 1440K due to the combustion takes place on that inner surface .From the inner surface of furnace to the outer wall shell temperature gradually reduce and the RL and the SC interface temperature found to be 398K ,

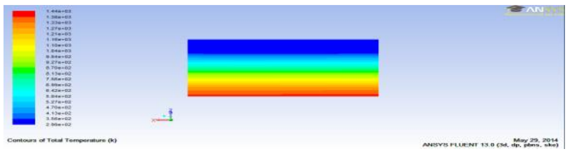
Initially inlet temperature of the fluid taken as 299K,innersurface temperature taken as 1440K and after the simulation outlet temperature found to be 306.8K ,temperature difference become 7.8K.Fig 4.1. (ii) to (v) shows the SCRL various cross.sectional views.



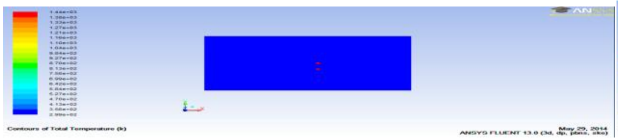
(i) .



(ii)



(iii)



(iv)

(v)

Fig. 4.1 SCRL 3D model of 0.65m refractory thickness (i) Isometric view (ii) Side view (iii) Top view (iv) Front view(minimum temperature) (v) Rear view(maximum temperature).

We have drawn four lines (Line A, Line B, Line C ,Line D)on the inner face of the stave which is adjoin on the interface of the SC and RL, with the different stave and refractory materials. Stave has safe temperature (ST) limit of 400K (taken from RSP data center).

In this graph ,show the inner face temperature along the length of the stave body, we have taken stave materials are cast iron ,aluminium and copper along with the refractory thickness of 0.65m,0.60m and 0.55m and in the graph 1,2,3 indicate cast iron line ,4,5,6 indicate Aluminium line and 7,8,9 indicate Copper line respectively,

Figure 4.2 graph drawn corresponding to the inner face of the stave line A ,The refractory thickness variation of 0.65m along the stave material; it has been observed that all the lines(3,6 and 9) are below the safe temperature(ST) lines but cast iron temperature is maximum compared to other materials, which is desirable. At the thickness reduced to 0.60m,cast iron temperature line(2) fluctuating on the (ST),which is not desirable and other lines(5and 8) are below ST line. Similarly at the thickness 0.55m, cast iron line (1) goes beyond the ST lines which is not desirable, aluminium and copper line(4 and 7) are below ST line (which is desirable).

Similarly from the figure.4.3 graph shows corresponding to the inner face of the stave line B. we can observed that cast iron line (1) at a thickness of 0.55m is near the ST line which is not desirable and other lines are below the ST line. It has been observed that aluminium and copper stave material has always maintain below ST line , Among these three stave materials copper has high heat dissipation rate .we had seen that cast iron is very nearly the ST line, further reduction of thickness would damage the stave and also increase the relining period. As the refractory thickness reduce temperature variation along the SCRL found to be enhanced.

Variation of the inner face temperature along the stave length is plotted **in Figs. 4.2 and 4.3,** considering different stave materials and different refractory thickness.

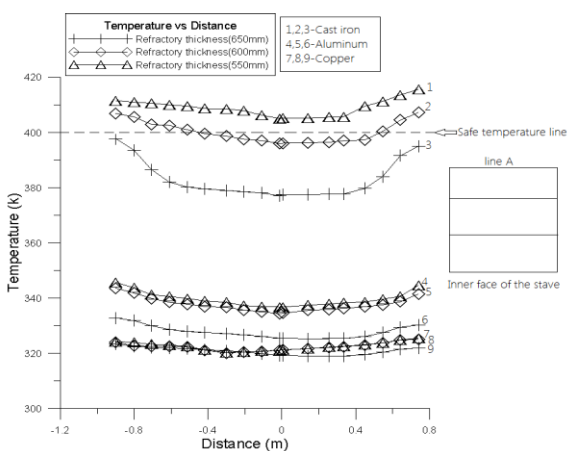


Fig.4.2

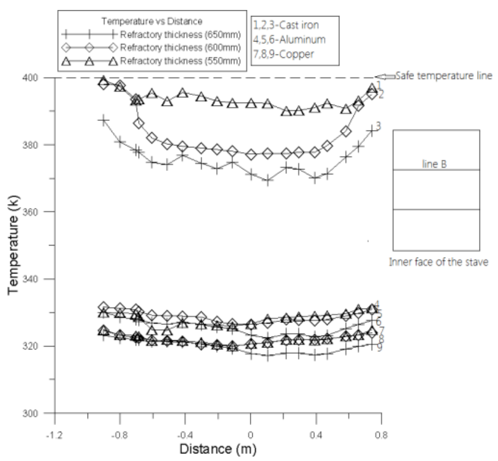
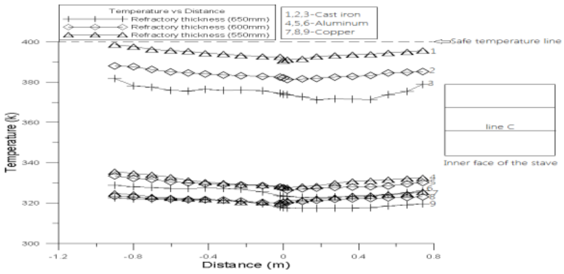


Fig.4.3

Figure 4.4, graph shows corresponding to the inner face of the stave line C, from this graph we seen that all the lines are below safe temperature line .because line C is close to the middle of the stave an also closer to the coil of the stave ,hence quickly heat dissipated . all other pattern remain same ,cast iron lines are closer to the ST limit due to less thermal conductivity than that of the other two materials. hence cast iron is not suitable for this purpose.

Figure 4.5 similar patterns being observed, taken inner face of the stave line D is away from the cooling coil their heat dissipation is very less, usually the aluminium and copper temperature variation has below the ST limit due to their high conductivity .

Fig. 4.4 and fig. 4.5 shows that Inner face temperature variation along the length of the stave with different stave materials and refractory thickness.



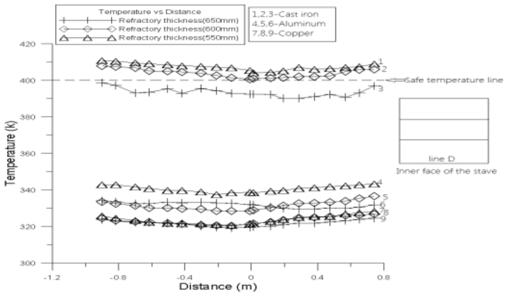
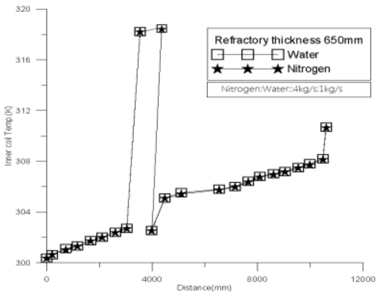


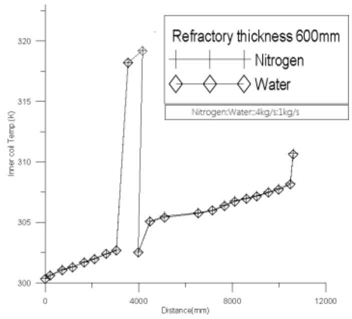
Fig. 4.4 Fig. 4.5

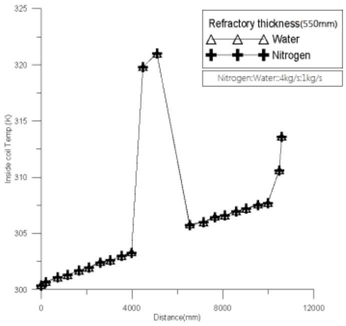
Fig.4.6 shows that the temperature variation along increasing coil length having refractory thickness of 0.65m using dissimilar cooling agent nitrogen and water. It is observed if we take mass flow rate of liquid nitrogen 4 times than that of cooling water, similar result would be obtained.

It is seen that temperature gradually enhance along the length of the coil. While closed to the end of the stave heat enhance slowly, at the interface corner of stave and refractory have identified the rapidly excessive increasing in temperature. The abruptly temperature slumps down while close to the outlet. at last, the exit temperature being slight higher than that of the entry temperature due to heat absorption in the whole process

Same observable fact has been also observed during simulation of having thickness of 0.6m and 0.55m as shown in Figs.4.7 and 4.8 respectively.







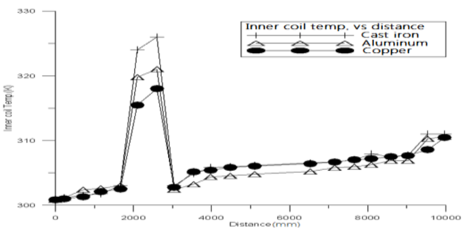
(Figure 4.6 Coil temperatures Along the length of the stave coil , Refractory thickness 0.65m)

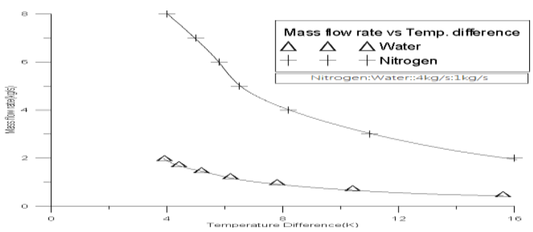
(Figure 4.7 Coil temperatures along the length of the stave coil Refractory thickness 0.6m)

(Figure 4.8 Coil temperatures along the length of the stave coil Refractory thickness 0.55m)

Generally the inlet temperature of the coils is taken as 300K. Fig.4.9 we have been observed that outlet stave coil temperature are one and the same for all the three stave. Though the Fig. depicts a sudden augment at a exacting point in all the three coils. It is found that maximum temperature rise in cast iron coil followed by aluminium and copper coil respectively.

Depicts the mass flow rate of cooling water and liquid nitrogen in the coil w. r. t. the temperature difference (dT) is plotted in fig.4.10. In this analysis we have taken the mass flow rate of liquid nitrogen is four times than that of the cooling water, however it is observed that difference of temperature occur identical for the water and nitrogen.





(fig. 4.9 Coil temperatures along length of the stave)

(fig. 4.10 Mass flow rate versus temperature difference)

Conclusions

This analytical and numerical research work has been done on 3D cooling stave with RL .the Analytical and numerical result almost similar. From this outcome we can be concluded that: Instead of cast iron If we use copper and aluminum as stave material,heat extraction rate from the refractory to the cooler stave would be Increase and the factor of safety of the cooling stave material will be enhancing ,because of higher thermal conductivity. As a result, the stave cooler would be sustain for long time and also relining period of the RL to be enhance. furthermore production rate would be high and cost of relining and manpower to be decrease significantly.As the mass flow rate of liquid nitrogen four time than that of cooling water, desirable results would be obtained, as compare to water due to plenty of liquid nitrogen in the industrial wastage.

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