Thermal Analysis of Blast Furnace Cooling Stave Using CFD

Manmohan Soni, Sankalp Verma

Abstract*: Blast furnace Cooling Systems have been developing since 1884. Earlier (till 1920's) the cooling was applied only to hearth and bosh areas. By 1930's and 1940's, cooling was also applied to the shaft. Simultaneously, external cooling methods like shower and jacket cooling of the furnace shell were tried. This method relied on extracting the heat through the furnace shell to the cooling medium, generating high thermal stresses during the heat transfer and hence jeopardizing the integrity of the shell. The main purpose of cooling system is to enhance the furnace campaign life. If heat transfer, thermal stress and furnace campaign life all such parameters should not be analyzed it may lead to catastic failure of Blast furnace. This Paper deals with the computational analysis of three-dimensional model of blast furnace stave, using FEV tool ANSYS FLUENT. Where the inner wall are heated up linearly, due to molten metal inside the furnace and the outer wall is been exposed to ambient condition with the maximum temperature TH and the minimum temperature with Tc The present computational investigation deals with Heat transfer analysis in blast furnace cooling stave and the parametric analysis such as the cooling channel inter-distance and diameter, coating layer on the external surface, cooling water velocity, etc is been done and the effect of them in heat transfer of stave or stave performance is been justified. The temperature distribution and flow pattern across the cavities were visualized. The FEV results are validated with well published results in literature and furthermore with experimentation. Results are first presented in the form of streamlines, isotherm contours, thermal stress, and Temperature difference.

***Index Terms*— Blast Furnace Stave, CFD, Heat Transfer.**

I. INTRODUCTION

A blast furnace is a type of metallurgical furnace used for smelting to produce hot metal. In a blast furnace, fuel and ore are continuously applied from the top and hot air is blown through the tuyeres inside the furnace so that the chemical reactions take place throughout the furnace. As the material moves downward the hot air comes in contact with coke thereby producing carbon monoxide which is responsible to reduce the ore to produce iron(molten metal). The end products are molten metal and slag which is tapped from the tap hole and is separated in the runner. The flue gases exit from the top of the furnace through the dust catcher and then it enters to the gas cleaning plant where it is cleaned and is fed to the gas main network. this cleaned gas is used as a fuel throughout the plant.

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Blast furnace Cooling Systems have been developing since 1884. Earlier (till 1920's) the cooling was applied only to hearth and bosh areas. By 1930's and 1940's, cooling was also applied to the shaft. Simultaneously, external cooling methods like shower and jacket cooling of the furnace shell were tried. This method relied on extracting the heat through the furnace shell to the cooling medium, generating high thermal stresses during the heat transfer and hence jeopardizing the integrity of the shell. The main purpose of cooling system is to enhance the furnace campaign life. If heat transfer, thermal stress and furnace campaign life all such parameters should not be analyzed it may lead to catastic failure of Blast furnace.

In 1987 blast furnace process has been studied by numerous researchers for many years, a variety of problems still remain unsolved concerning the rates and mechanisms for the phenomena occurring in the furnace. The major reason for this is that the blast furnace process includes many physical and chemical changes which occur simultaneously. A number of attempts have, however, been made to develop mathematical models for the better understanding of this complicated process. [1]

In1989 Takano and Kitauchi implement 145mW145-MW blast furnace gas firing gas turbine combined cycle plant was designed and installed in a steel works and improve efficiency 45% of thermal plant.

Tasuku and Hanabuchi 1991 describe the the various kinds of processes used in manufacturing industries are generally comprised of processing units and comparative nalysis is been done.

In 1999 Tare and Growcock discusses the effect of incorporating blast furnace slag (BFS) as an additive in water-based drilling fluids.

Vernengo and Milanovic 2003 simuate blast furnace hearth using CFD model and analyzed wearing profile.

Elsaadawy and lu 2005 studied a mathematical model of the tapping process in there model the effect of the coke-free layer height on the flow pattern and bottom wall shear stress distributions is investigated. Also, the effect of the taphole height is considered in other wards, the effect of the sump ratio is studied.

In 2007 Cheng and Liang develop a monitoring method which is combination of "inverse problem" and the concept "non-inverse problem", for copper stave and it is used to calculate online the accretion thickness and temperature of hot surface of copper staves after obtaining the values of thermocouples of copper staves.

Ning and CHENG in 2010 study the effect of gas temperature variation on cooling stave, temperature, stress and displacement distributions of cooling stave were analyzed

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respectively when gas temperature inside blast furnace increases from 1000 to 1600 °C. Tong and CHENG 2012 develop a mathematic model of calculating accretion thickness by heat flow of BF is proposed, and[22] the calculated results indicate that accretion thickness could be kept at a reasonable range of around 50 mm by controlling heat flux around 22.0 kW/m2.

ZHANG 2013 enhances the campaign life of blast furnace. Double row cooling pipe high efficiency cooling stave was developed which could prolong the service life of bosh, belly and stack. Hot pressed carbon brick and ceramic cup hearth lining structure were applied and optimized

II. THEORY

The geometry of the problem herein investigated is depicted in Fig.

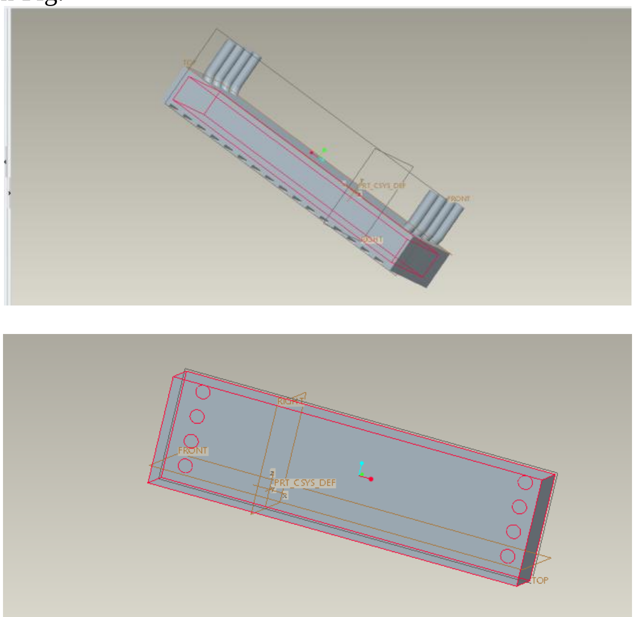
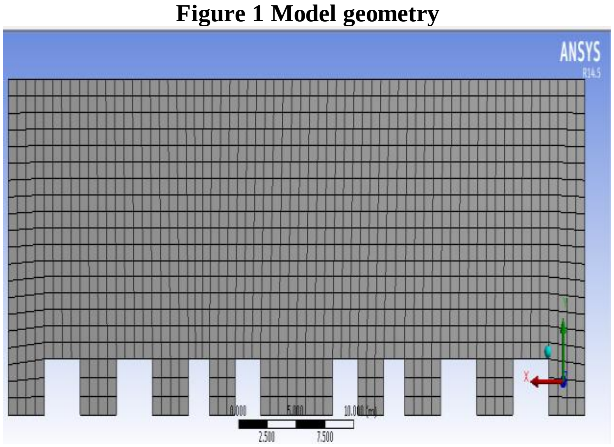
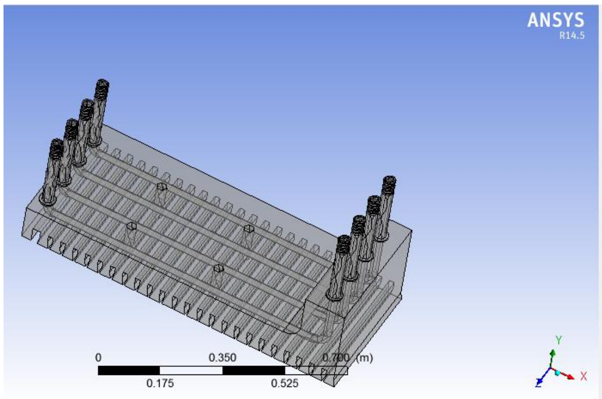


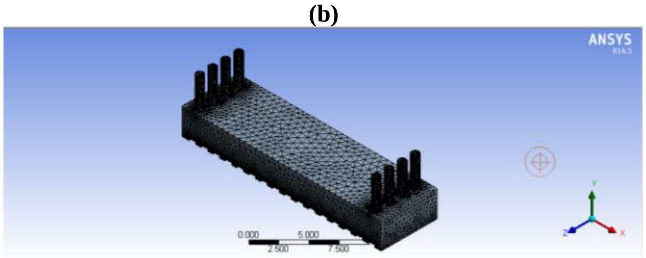
Figure 1 Model geometry



(a)



(b)



(c)

Figure 2 Mesh Configurations

In system modeled blast furnace stave is analyzed using Fluent. Temperatures of the hot (Bottom) and cold (top) walls are listed as constants, i.e., T1 and T0 respectively, while the top and bottom are adiabatic.

The equations governing this problem are those of Navier-Stokes along with the energy equation. The Navier-Stokes equations are applied to incompressible flows and Newtonian fluids, including the continuity equation and the equations of conservation of momentum on the x and y According to equations

$$\frac{\partial u_2}{\partial t}+u_1\frac{\partial u_1}{\partial x_1}+u_2\frac{\partial u_1}{\partial x_2}=$$

$$-\frac{1}{\rho}\frac{\partial \rho}{\partial x_2}+\nu\left(\frac{\partial^2 u_1}{\partial x_1^2}+\frac{\partial^2 u_1}{\partial x_2^2}\right)+g\beta(T-T\infty)$$

$$\frac{\partial u_1^*}{\partial x_1^*}+\frac{\partial u_2^*}{\partial x_2^*}=0$$

x1 momentum equation

$$\frac{\partial u_1^*}{\partial t^*}+u_1^*\frac{\partial u_1^*}{\partial x_1^*}+u_2^*\frac{\partial u_1^*}{\partial x_2^*}=-\frac{\partial p^*}{\partial x_1^*}+\Pr\left(\frac{\partial u_1^*}{\partial x_1^*}+\frac{\partial u_1^*}{\partial x_2^*}\right)$$

x2 momentum equation

$$\frac{\partial u_2^*}{\partial t^*}+u_1^*\frac{\partial u_2^*}{\partial x_1^*}+u_2^*\frac{\partial u_1^*}{\partial x_2^*}=-\frac{\partial p^*}{\partial x_2^*}+\Pr\left(\frac{\partial u_2^*}{\partial x_1^*}+\frac{\partial u_2^*}{\partial x_2^*}\right)$$

$$+Gr\Pr^2 T^*$$

Energy equation

$$\frac{\partial T^*}{\partial t^*}+u_1^*\frac{\partial T^*}{\partial x_1^*}+u_2^*\frac{\partial T^*}{\partial x_2^*}=\left(\frac{\partial^2 T^*}{\partial x_1^{*2}}+\frac{\partial^2 T^*}{\partial x_2^{*2}}\right)$$

Where Gr is the Grashof number given as

$$Gr=\frac{g\beta\Delta TL^3}{\nu^2}$$

Boundary Condition

Value of hk

The overall coefficient of heat convection between furnace shell and atmosphere is given by

$$h_k = h_{k1} + h_{k2}$$

where hk1 is the coefficient of natural heat convection between furnace shell and atmosphere; hk2 is the radiative coefficient of heat convection between furnace shell and atmosphere, W/(m2 oC).

For the calculation of hk1, an equation can be described as followings according to the rule of natural heat convection:

$$Nu = C(Gr \cdot \Pr)^n$$

Therefore, the value of hk1 is given as

$$h_{k1} = Nu\frac{\lambda_{air}}{l} = C(Gr \cdot \Pr)^n \frac{\lambda_{air}}{l}$$

where kair is the thermal conductivity coefficient of atmosphere, W/(m0C); Pr Prandtl number; Gr Grashof number; Nu Nusselt number; l characteristic length of heat surface, m; c, n constant, can be obtained by checking.

Convection heat resistance between cooling water and steel pipe

R1 =(1/αw)

where aw is the coefficient of heat convection between cooling water and steel pipe.

$$Nu = \alpha_w d_1 / \lambda_w = 0.023(vd_1 / v)^{0.8}(v/\alpha_w)^{0.4}$$

$$\alpha_w = 0.023(v^{0.8}\lambda^{0.6}c_p^{0.4}\rho^{0.4})/(d_1^{0.2}/v^{0.4})$$

III. NUMERICAL METHOD

In order to model the problem, the computational modeling and simulation of the numerical is done with the help of ANSYS-FLUENT. In this software platform the numeric simulation of 3D problems involving fluid flow and heat transfer. Boundary condition are given then simulated, which is shown in figure 3 and 4 and The program operates for incompressible flow, Newtonian fluid with and without heat transfer, utilizing the Boussinesq approximation in rectangular coordinates (x, y). And with the help of it various temperature profile and isotherms figures are generated and demonstrated in this paper.

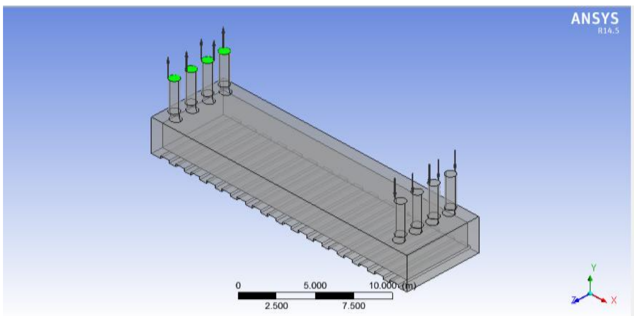


Figure 3 Inlet and outlet boundary Condition

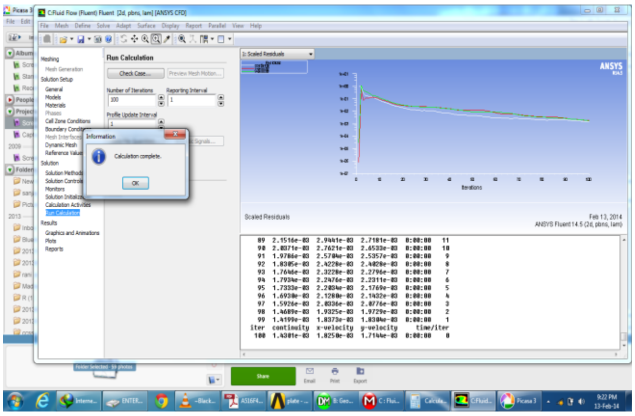


Figure 4 Simulation of model in all given boundary condition.

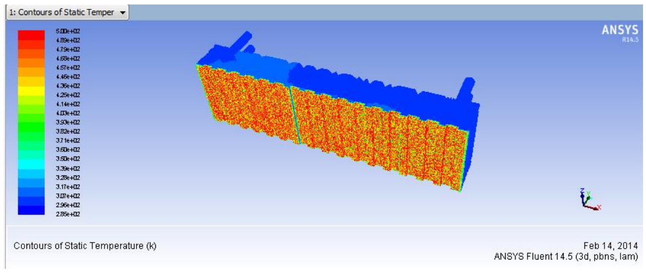
IV. RESULT

The accuracy of the numerical model and Computational model was verified by comparing results from the present study with those obtained by Wu Lijun [20] for heat transfer for blast furnace stave

Table 1 Validation of dimensionless stream function in the case of trapezoidal cavity

Water Speed m/s	Water Temperature	Measuring Point Temperature	Expt. Ref[16]	Simulated Ref.[20]	Present ANSYS
1.5	23	131	465	472	470
2	32	143	506	519	518.7
3	35	145	526	531	530
4	40	151	558	551	552

Table 1 shows the close and good agreement on comparing results from the present study. The blast furnace stave is model is simulated and verified and compare with the experimental data and considering other parameter such as water speed, water temperature , stave body thickness, bricks thickness etc. are considered and results are generated. This energy balance is been verified by this references in all cases considered here.



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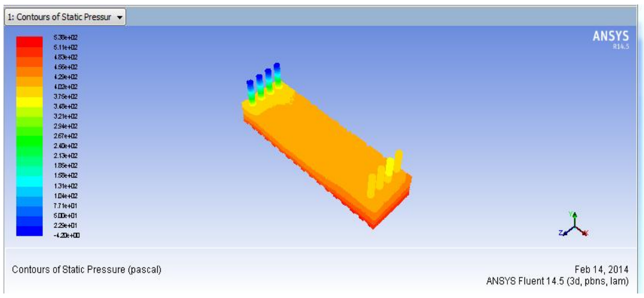

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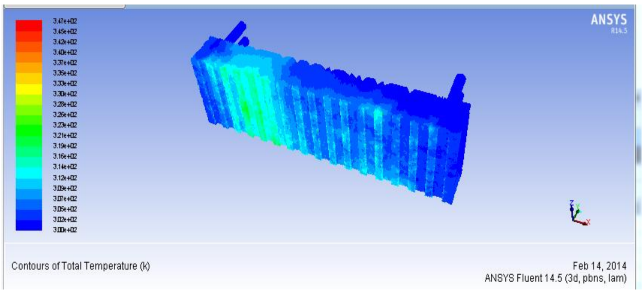

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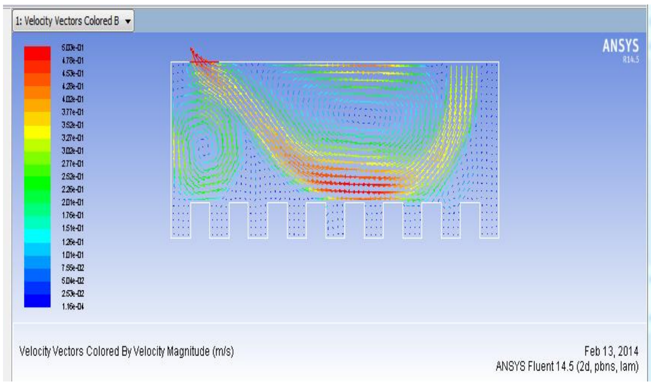

d

Figure 5 Blast furnace staves deformation diagram and flow pattern inside the stave

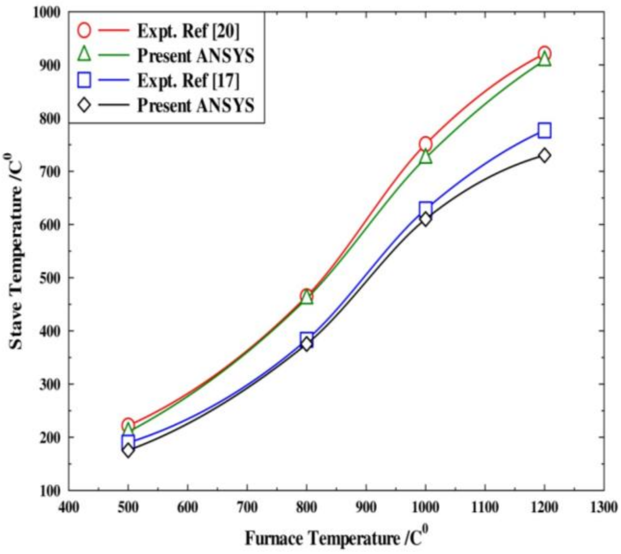

Figure 6 Blast furnace stave temperature variation at different location

During operation in blast furnace there is difference in temperature at different location from top to bottom staves are located around the blast furnace in order to maintain proper temperature inside the furnace and inlaid brick are exposed to high temperature and pressure due to which they get deformed and heat is transfer to stave inner surface which is in direct contact with brick since these stave are also cooled with the help of water.

Figure 5 shows the Blast furnace staves deformation diagram and flow pattern inside the stave and figure 6 shows the Blast furnace stave temperature variation at different location are compared with present result and shows good agreement.

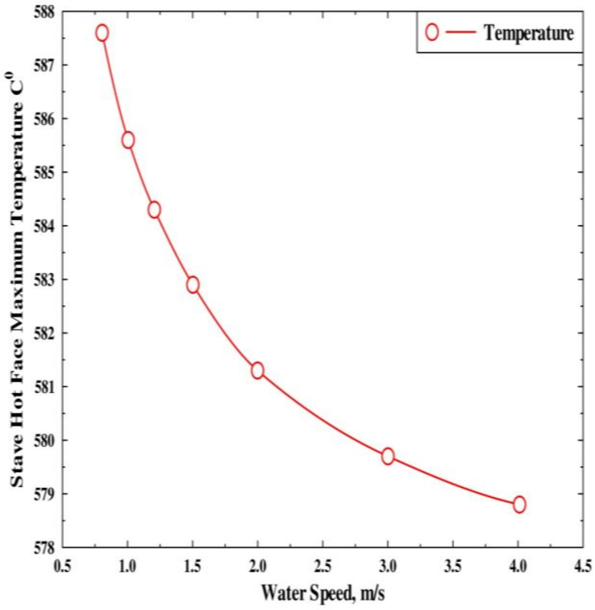

Figure 7 Variation of the cooling water velocity on maximum temperature of the stave hot face

In figure 7 it can be seen that the cooling water velocity has an influence on the maximum temperature of the stave hot face.

It can also be conclude that cooling water velocity effect film boiling. If film boiling occurs more heat supplied through stave to water and than it can be evacuated by bulk water.

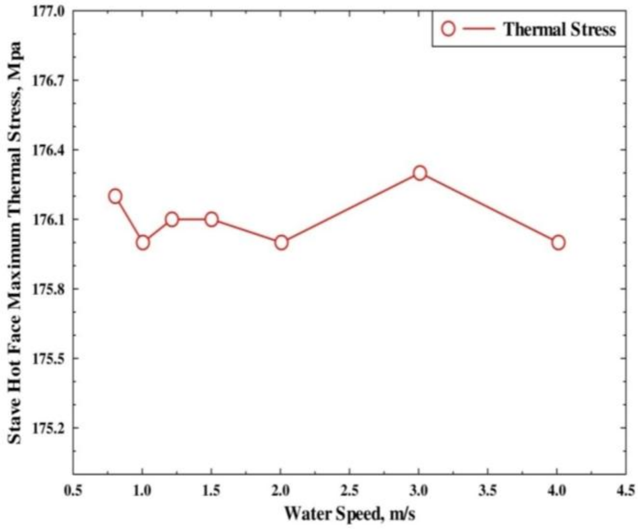

Figure 8 Variation of the cooling water velocity on thermal stress of the stave hot face

Figure 8 it can be seen that the cooling water velocity has an influence on the maximum temperature of the stave hot face but not much influence on the thermal stress of the stave.

Little bit variation is seen from the table on thermal stress that can be considered as negligible.

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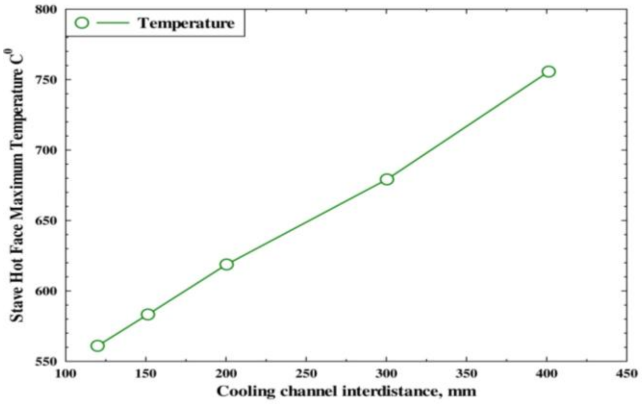

Figure 9 Variation of effect of the cooling channel interdistance on maximum temperature of the stave hot face

Figure 9 shows the effect of the cooling channel inter distance on maximum temperature of the stave hot face. From theses it seems that that on increasing cooling channel inter-channel distance stave temperature goes on increasing linearly. It has been also notice that on increasing channel distance there is linearly 3-8% of increase in temperature.

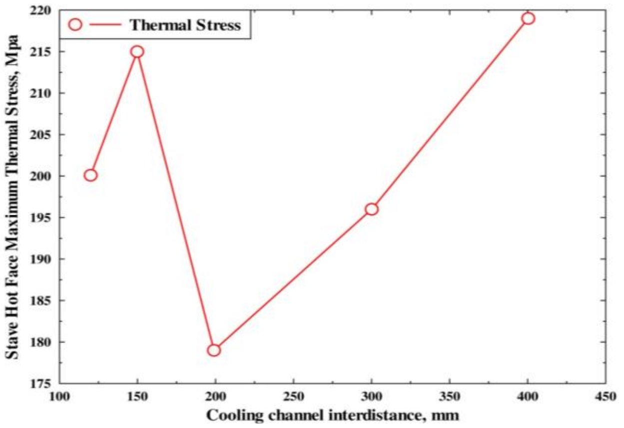

Figure 10 Variation of effect of the cooling channel interdistance on thermal stress of the stave hot face.

From Figure 10 the effect of the cooling channel inter distance on thermal stress of the stave hot face has been visualized and from these it can be revealed that cooling channel inter-distance has a great influence on the stave.

As on increasing channel distance thermal stress first increases up to 150mm, then sudden decline is seen at 200mm and then afterwards thermal stress goes on increasing rapidly. It can also be conclude that at 200mm is optimum cooling channel inter distance.

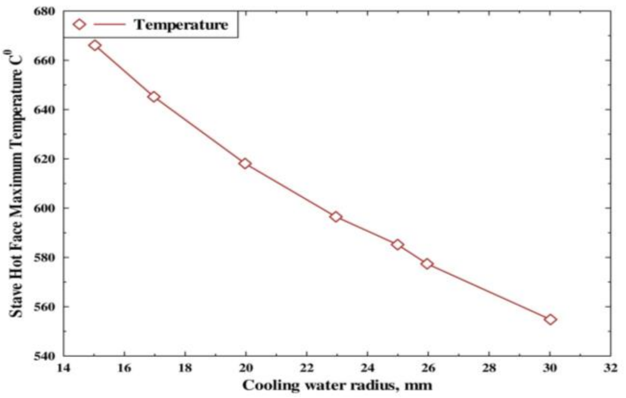

Figure 11 shows the effect of the cooling radius on maximum temperature of the stave hot face.

It seems that on increasing cooling water radius stave temperature goes on decreasing linearly.

It can also be conclude that there is 3-4% decline in temperature in concern with pervious parameter. The total decline is around 16%.

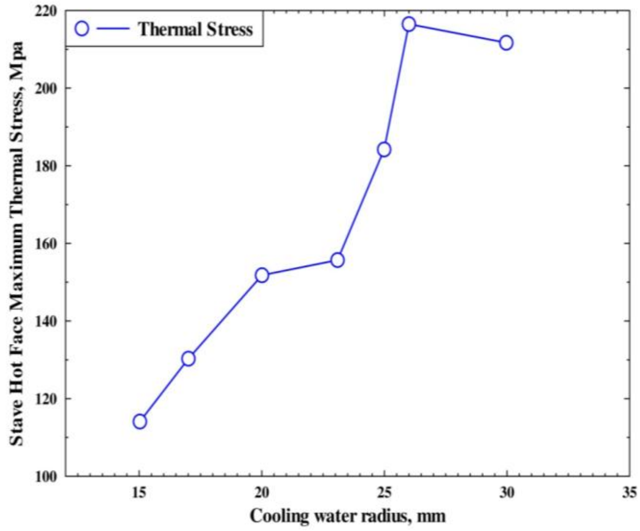

Figure 12 shows the effect of the cooling water radius on thermal stress of the stave hot face.

In figure 12 there is decline in stave temperature, but here the thermal stress increases with the increment of the cooling channel radius. The location of the maximum thermal stress does lie on the surface of the stave hot face, on the interface between cooling water pipe and stave body. It is because of that the temperature gradient increases between cooling water pipe and stave body

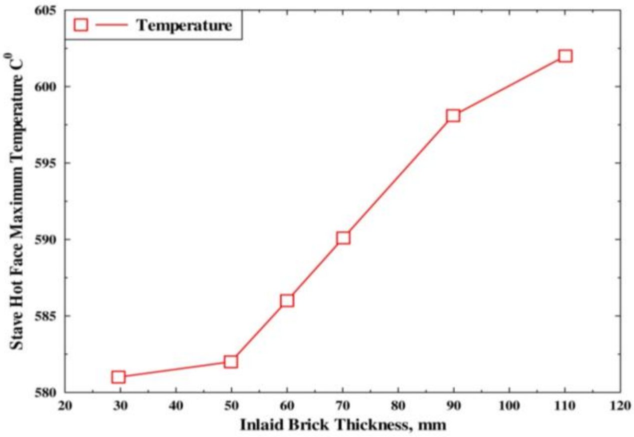

Figure 13 Variation of the inlaid brick thickness on maximum temperature s of the stave hot face.

The effect of the inlaid brick thickness on maximum temperature of the stave hot face is shown in Table and Figure. From this it can be conclude that on increasing brick thickness temperature linearly goes on increasing, apart from that the inlaid bricks glued into the dovetail grooves provided a sort of ‘‘shading’’ of the front face of the steel ribs.

However, the temperature gradient between steel and inlaid brick will increase as adding inlaid brick thickness. The ‘‘shading’’ will be losted when the inlaid brick thickness is more than some value.

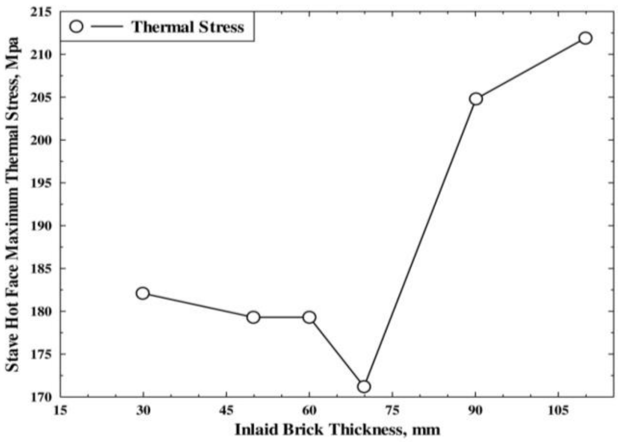

Figure 14 Variation of the inlaid brick thickness on thermal stress of the stave hot face.

Figure 14 illustrated that the inlaid brick thickness has a large influence on the thermal stress of the stave hot face. At 70 mm the thermal stress is minimum and yields at maximum thermal stress shown in curve.

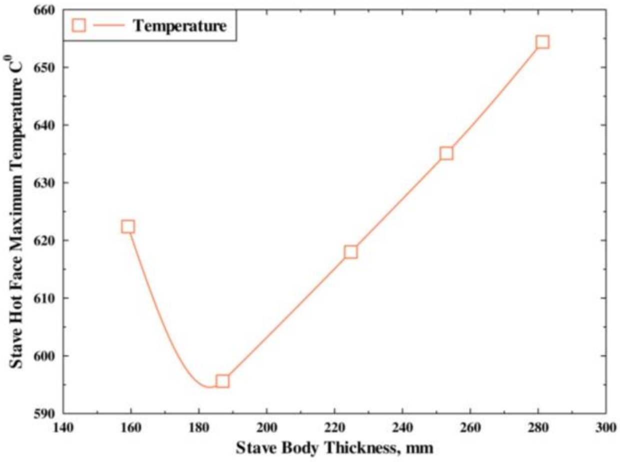

Figure 14 Variation of the stave body thickness on maximum temperature of the stave hot face.

Figure 14 the effect of the stave body thickness on maximum temperature of the stave hot face have been visualized that the maximum temperature and thermal stress–stave body thickness curve both have the yielding point when stave body thickness is 180 mm. At this point, the value of the temperature and thermal stress is minimum. As we known, the thicker the stave body, the higher the thermal resistance of the stave body will become.

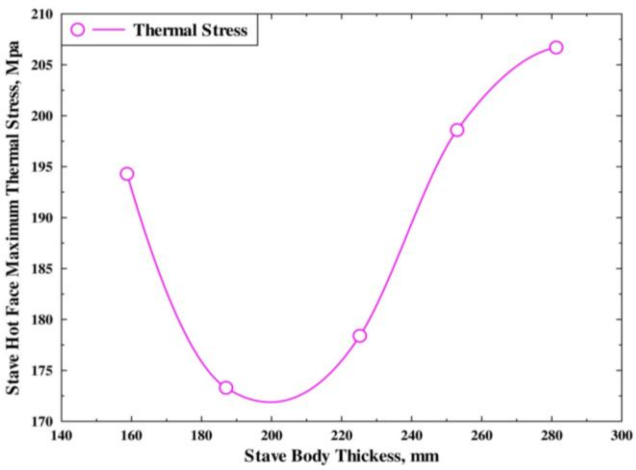

Figure 15 Variation of the stave body thickness on thermal stress of the stave hot face.

In figure 15 shows the effect of the stave body thickness on thermal stress of the stave hot face. From these we conclude theas we goes on increasing body thickness thermal first decreases upto 200 mm thickness and then after ward stress starts increasing moderatly.

From it can be revealed that the otimization thickess of stave should be in range of 160 to 220 mm for better performance and better life.

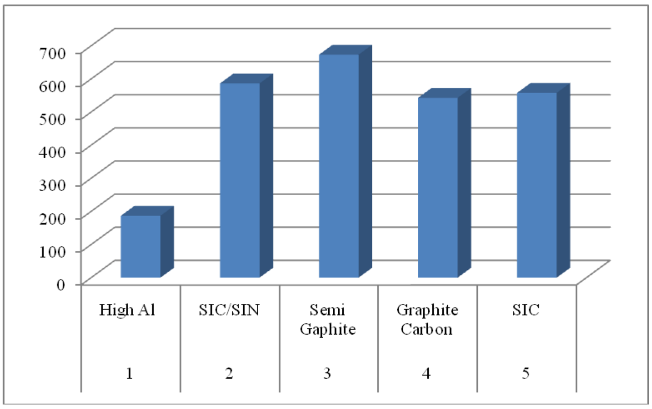

Figure 16 Variation of different lining material on maximum temperature of the stave hot face

On applying different brick lining material the maximum temperature of the stave hot face is been analyzed and illustrated in figure 16 from this we conclude that on applying semi graphite material lining can withstand maximum temperature and simultaneous lowest for aluminum. In different places and location on considering furnace thermo economic other material are used such as SIC, graphite carbon, etc It can also be revealed that the flexural and compress strength of the high alumina brick is the lowest compared with other refractory bricks, it annot suit to the adverse circumstances like scouring of the high temperature and melting slag and iron; friction and impact of the blast furnace charge and penetrating of the alkali metals.

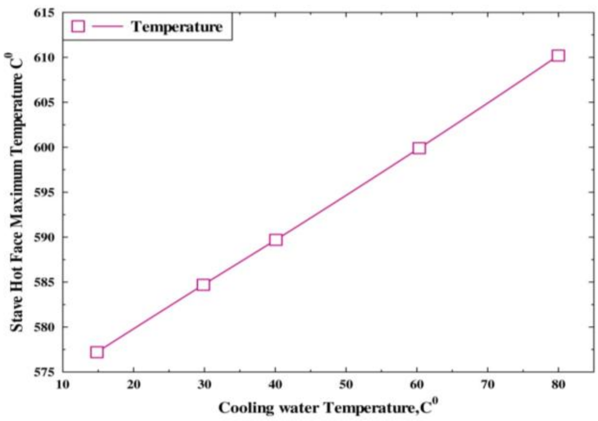

Figure 17 Variation of cooling water temperature on maximum temperature of the stave hot face.

Table 6.13 Figure 6.14 shows the effect of cooling water temperature on maximum temperature of the stave hot face. It can be seen that water temperature has a linear influence on the maximum temperature of the cooling stave. However, seeking for the lowest possible water temperature would be uneconomical. The water temperature can be chosen according to the local conditions, i.e. between 30 and 40 ^{0}C.

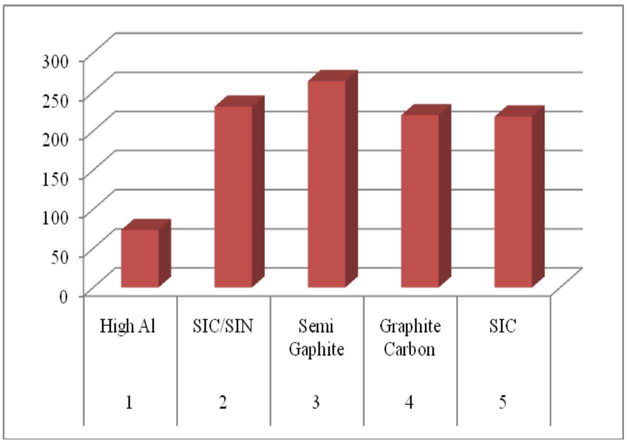

Figure 18 Variation of different lining material on thermal stress of the stave hot face.

Figure 18 exemplify that the value of thermal stress of the stave hot face is the highest by using the semi-graphite carbon brick lining, higher by using silicon nitrogen bond silicon carbide brick, graphite carbon brick and silicon carbide brick, the lowest by using high alumina brick.

Due to having low the flexural and compress strength in high Alumina bricks they are rarely used as compared to other refractory bricks.

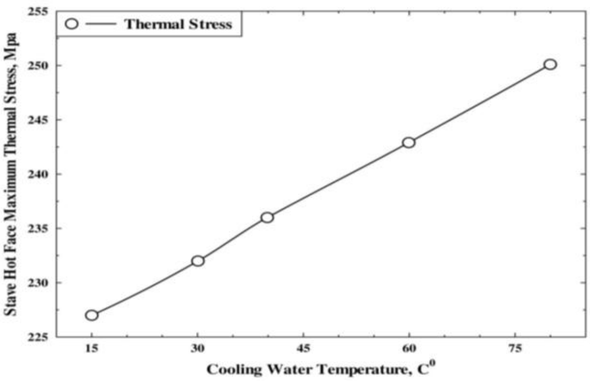

Figure 19 Variation of cooling water temperature on thermal stress of the stave hot face.

From Figure 19 illustrate that water temperature has a linear influence on the thermal stress of the cooling stave. However, seeking for the lowest possible water temperature would be uneconomical. The water temperature can be chosen according to the local conditions, i.e. between 30 and 40 ^{0}C.

V. CONCLUSION

It is found that reducing the water temperature and increasing the water velocity would be uneconomical. The heat transfer and hence the maximum temperature and thermal stress in the stave can be controlled by properly adjusting operating conditions of the blast furnace, such as the gas flow, cooling channel inter-distance and diameter, lining material, coating layer and gas clearance

The thicker the stave body, the higher the thermal resistance of the stave body will become.

It can also be revealed that the flexural and compress strength of the high alumina brick is the lowest compared with other refractory bricks, it cannot suit to the adverse circumstances like scouring of the high temperature and melting slag and iron; friction and impact of the blast furnace charge and penetrating of the alkali metals.

The best choice for lining material is silicon nitrogen bond silicon carbide brick or silicon carbide brick.

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