Study on blast furnace cooling stave for various refractory linings based on numerical modeling

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Abstract. Cooling technology for refractory lining of blast furnace is very important for the metallurgical industry, because it can substantially increase output and operation life of furnaces. A three dimensional mathematical model for the temperature field of the blast furnace stave cooler with refractory lining has been developed and analyzed. The temperature and heat dissipated by stave cooler is examined by using the finite element method. The cast steel stave is studied and computational analysis is made to know the effect of the cooling water velocity, temperature, and the lining material on the maximum temperature of the stave hot surface. The refractory lining materials, which are used in this experiment, are high alumina bricks with different stave materials (copper, aluminum and cast iron). The obtained numerical calculations are compared with that obtained from experiments performed at Rourkela Steel Plant, Odisha taking a stave in belly zone having maximum heat load shows very good agreement.

Keywords: Blast furnace; Stave; cooling; Refractory; Stave

1. Introduction
The blast furnace, mostly used in steel industries, is a multiphase reactor, which produces molten iron (Figure 1). It is basically a vertical shaft with height from 20 to 45 meter and diameter at bottom is about 12.0 meter. It is one of the most normally utilized iron producing procedure, for about 1800 cubic meters per year. The charging arrangements of blast furnace are at the top for ore, flux and coke and provisions at base to take out molten iron and slag. Hot air is blown through the tuyere, near the bottom of the furnace, increases the rate of combustion and sustains the required higher temperature for melting of iron.

The campaign life of the blast furnace very much affected by the properties of refractory Lining materials and decrease of its thickness due to erosion in the process. The cooling of refractory lining is the most contributing factor in deciding the Furnace campaign life. Lining cooling by stave is one of the results of such endeavours. A stave is a cooling gadget having one or more inside channel, and is introduced in numbers on the inward surface of a blast furnace. The staves are 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. The intense load of heat within the blast furnace is the lower stave area of a blast furnace with increased smelting. Normal service life of the lining brick in this zone is shorter than in other zone. Damaged cooling staves are among the fundamental significant causes that
prompt a remarkable redesign.

The major reason of overhaul or medium maintenance of a blast furnace is due to its damaged linings due to poor cooling staves. As a result, campaign period of a blast furnace principally depends on cooling stave life. Higher cost of copper staves in comparison to cast iron staves prohibits its use, although it has better thermal conductivity. Hence, steel staves are gaining wider acceptance because of its better properties, like, specific elongation, tensile strength, melting temperature and thermal conductivity. It is seen that thumb rules and/or wear of stave coolers are the major parameters on which it is designed and fabricated. With advance of finite element method, application of heat transfer calculations to the cooling stave of blast furnace is also become significant. There are different kind of mathematical models are applied by many researchers to know the effect of cooling stave, lining materials and cooling channels.

Pückoff and Knoche [1] have prescribed different guidelines and designed different plate coolers for heat extraction at blast furnace bosh, belly and stack regions. Changko et al. [2] have analyzed the thermal behaviour in upper tap hole area of the blast furnace and indicated that thermal properties of mud-core, convection heat transfer coefficient of cast and bricks of spool have a great effect on the top hole area temperature distribution. Shrivastava and Himte [3] have studied stave cooler of blast furnace using heat transfer analysis taking different skull and brick lining thickness. Steiger et al. [4] proposed a heat transfer model to calculate the temperature field of copper cooling plate and refractory lining. Gdula et al. [5] took different cooling system and lining material to analyze the heat transfer of the blast furnace hearth (bottom portion). A three-dimensional heat transfer model is reported by Wang et al. [6] to illustrate the temperature variation in the wall of the lower stack region of a blast furnace. Torrkulla and Saxen [7] have proposed a mathematical model for the prediction of wearing down and skull thickness of hearth in the blast furnace. They have used the thermocouples to measure the temperature at hearth and lining and show a model to predict the erosion of the lining and thickness of the skull. Verscheure et al.[8] have used a pyro-metallurgical processes to monitor and analyse the blast furnace temperature information to increase its campaign life. Peng et al. [9] used different lining thickness made of copper staves and sensor bars for their modelling. Their model showed the effect of skull and lining thickness on heat transfer from the staves. In their work, Chang et al. [10] gave emphasis on erosion in the hearth section of the blast furnace when molten metal is collected. They have analysed the process taking three different height for their observation; ie.,10 centimetres, 30 centimetres and 50 centimetres from the bottom of the blast furnace. Kumar et al. [11] have taken two different types of lining material, i.e., high alumina and silicon carbide and proposed a three dimensional model for the blast furnace stave. Lijun et al. [12] have used the finite element method to analyze the blast furnace and provide a three dimensional model. They observed that it is uneconomical to reduce the temperature of cooling water and increasing the velocity of water. David Roldan et al. [13] have performed a 3D analysis of furnace shell, refractory material, ram and hot metal. Cheng at al. [14] have designed copper stave for blast furnace and showed its effectiveness for blast furnace cooling. Fu et al. [15] have modelled the blast furnace considering all type of gas and mass in/out flowing and analysed the system using computational fluid dynamics.

![Fig. 1:- Schematic diagram of a blast furnace](image)
Literature survey of previous works indicate that most of works gave attention to the design parameter of stave cooler and cooling coil using simulation and analysed the stave cooler at different thermal load to calculate the critical temperature of hot surface of blast furnace stave. Very few works are reported on suitability of any other alternative medium to cool the refractory lining or a different material except copper and cast iron for design stave cooler. The present work describes a three-dimensional analysis for blast furnace cooling stave with linings to explore the possibility of an alternative cooling medium.

2. Modelling and analysis
Cast steel cooling stave and lining of a blast furnace situated at Rourkela Steel Plant, Odisha is taken for the present analysis. Figure 2 illustrates the three-dimensional schematic representation of the total setup. The staves are made of cast steel having a network of tubes (Figure 3) in which the cooling fluid circulates. Ansys® Fluent [16] on workbench environment is used for geometry and meshing of the model.

![Fig. 2:- Isometric view of cooling stave with refractory linings](image)

![Fig. 3:- Cooling pipe of stave cooler](image)

2.1. Blast furnace cooling stave and refractory lining
Dimensions of blast furnace cooling components and materials type are shown in Table 1 and Table 2 respectively. The cooling apparatus is usually comprised of slag skull, refractory lining, cooling stave, and filling materials at interfaces and furnace shell. There are passage holes for circulating cooling pipes inside the stave.

| Sl. No. | Part                | Length | Breadth | Height | Diameter       |
|--------|---------------------|--------|---------|--------|----------------|
| 1      | Furnace shell       | 25     | 800     | 1600   |                |
| 2      | Filling material    | 30     | 800     | 1600   |                |
| 3      | Stave               | 180    | 800     | 1600   |                |
| 4      | Refractory lining   | 600    | 800     | 1600   |                |
| 5      | Slag skull          | 40     | 800     | 1600   |                |
| 6      | Cooling pipe        | 8000   | Inner distance between channel=150 | ID-32, OD-40 |

2.2. Present formulation
Following assumptions are made to model the heat transfer of the lining and steel cooling stave for the present formulation:
(1) Steady-state conductive heat transfer process.
(2) It is assumed that skull is formed on the inner surface of refractory lining.
(3) Heat transfer resistances among furnace shell and filling material, stave and skull are neglected.
(4) Radiation heat transmitted from solid materials to inner surface of the stave is neglected.

Table 2: Materials used for different parts.

| Sl. No. | Part           | Material                  |
|---------|----------------|---------------------------|
| 1       | Furnace shell  | Steel                     |
| 2       | Filling material | Alumina paste             |
| 3       | Stave          | Cast steel                |
| 4       | Refractory lining | Alumina                  |
| 5       | Slag skull     | Mixture of Iron & slag    |
| 6       | Cooling pipe   | Steel                     |

The following equation is used to make a three-dimensional heat transfer analysis:

$$\frac{\partial}{\partial x} \left( k(T) \frac{\partial T}{\partial x} \right) = 0, \quad i = 1, 2, 3$$

(1)

Where, $k$ is the thermal conductivity coefficient in W/(m K), varies with temperature, $T$ represents temperature in K, $i$ represents $x$, $y$ and $z$ axis. Load and boundary conditions can be expressed as:

(a) Atmosphere temperature is 321 K and inlet water temperature is maintained at 305 K.

(b) Heat convection coefficients:

a) Between furnace shell and atmosphere -

$$k \frac{\partial T}{\partial x} = h_s (T_s - T_a)$$

(2)

where, $T_s$ and $T_a$ are temperatures of furnace shell and atmosphere respectively; $h_s$ is the overall coef. of heat convection between furnace shell and atmosphere, is taken as 12 W/(m² K).

b) Between water and inner sides of the cooling pipe -

$$k \frac{\partial T}{\partial n} = h_{pw} (T_p - T_w)$$

(3)

where, $T_p$ the contact temperature between cooling stave and cooling water pipe, $T_w$ cooling water temperature, $h_{pw}$ the integration coefficient of heat convection between cooling stave and cooling water, is taken as 8000 W/(m² K). Where, $h_{pw} = \frac{1}{R}$ $R$ is the total heat resistance between cooling water and stave body.

c) Between slag skull and hot air temperature –

$$k \frac{\partial T}{\partial x} = h_k (T_k - T_h)$$

(4)

where, $T_k$ is the slag skull temperature, $T_h$ the hot air temperature, $h_k$ the coefficient of heat convection between slag skull and high temperature hot air is taken as 320 W/(m² K) as prescribed by Plyashkevich et al. [17].

d) The properties of materials used in the analysis are shown in Table 3.
To show the validity and reliability of the model, temperature field of the cast steel cooling stave and linings of a blast furnace situated at Rourkela Steel Plant, Odisha is identified and the stave temperatures estimated by heat transfer model are compared with the temperatures measured by thermocouples during an actual production stage.

Table 3:- Materials properties.

| Sl. No. | Part                  | Density, $\rho$ (kg/m$^3$) | Thermal conductivity, $k$, (W/m°C) | $C_p$ (J/kg°C) | Young’s modulus (Pa) | Poisson ratio | Coeff. Linear th. expansion, $\alpha$/°C |
|---------|-----------------------|----------------------------|-----------------------------------|----------------|----------------------|--------------|----------------------------------------|
| 1       | Furnace shell         | 7840                       | 52.2-0.25t                        | 465            | $1.7 \times 10^{11}$ | 0.3          | $1.05 \times 10^{-5}$                 |
| 2       | Filling material      | 350                        | 0.33                              | 875            | $2.1 \times 10^{10}$ | 0.1          | $4.7 \times 10^{-6}$                  |
| 3       | Stave                | 7810                       | 52.2-0.25t                        | 500            | $1.7 \times 10^{11}$ | 0.3          | $1.05 \times 10^{-5}$                 |
| 4       | Refractory lining     | 2700                       | 2.09+0.002t                       | 1300           | 1.6                  | 0.25         | $7.8 \times 10^{-6}$                  |
| 5       | Slag skull           | 2000                       | 1.2                               | 983            | $2.1 \times 10^{10}$ | 0.1          | $4.7 \times 10^{-6}$                  |
| 6       | Cooling pipe         | 7800                       | 52.2-0.25t                        | 480            | $1.7 \times 10^{11}$ | 0.3          | $1.05 \times 10^{-5}$                 |

$t$ is material temperature, °C.

3. Results and discussion

Figure 4 shows the temperature variation inside the cast iron stave body with water as a cooling agent and alumina refractory lining of 650 mm thickness. It displays that although the hot surface of refractory lining is 1440K, it reduces to 397K at stave when cooling water has inlet and outlet temperature are of 300K and 307.8K respectively. Figure 5 gives the temperature decrease from brick to stave, indicating cooling of stave is faster than bricks. From Figure 6, it is apparent that the temperature of stave decreases as refractory thickness increases when mass flow rate of coolant is 5 kg/s. It illustrates that both the factors, material of stave and as well as cooling channel position and coolant, affects the life of refractory lining and stave.

Figure 7 shows the temperature variation inside the stave body for different lining materials and thickness along middle of the stave. It illustrates that both factor affects the stave life as well as cooling channel position. Among the three materials copper was found to be the best material.
Fig. 6.- Temperature variation with refractory thickness where mass flow rate is 5 kg/s

Fig. 7.- Temperature variation inside the stave body at the middle surface

Fig. 8.- Coil temperature variation with distance for lining of 600 mm thickness

Fig. 9.- Temperature variation with mass flow for different cooling medium

Figure 8 demonstrate the variation of temperature with increase in length of the coil when nitrogen and water are used as cooling agent for refractory thickness of 600mm. It is observed that with increased mass flow rate of nitrogen by four times same cooling effect can be obtained as that of water. Comparison shown in Figure 9, when mass flow rate of nitrogen is 10 times than water one can get much advantage over water.

4. Conclusion
The three-dimensional mathematical model of temperature stress field of cooling stave and lining has been calculated by using finite element method based on the heat transfer analysis. The results indicate
that lining materials and lining thickness have large influence on temperature field at stave, subsequently on its life. The findings obtained can be successfully used to optimize the lining thickness for a particular lining material. It is also found that nitrogen, which is a by-product of the steel plant can be used as an alternative cooling medium with increased flow rate.

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