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Computational Study of Blast Furnace Cooling Stave using Heat Transfer Analysis

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***Abstract*: Reliable furnace cooling technology is a domain of increasing concern to the metallurgical industry as it can significantly increase process intensities, productivity and campaign times of furnaces. Although there are many advantages in using cooling systems, they also impose a variety of problems mainly related to safety, heat losses and sustainability of the operations. The choice of cooling system is hence a matter of trade-offs and differs for every metallurgical application.**

This paper gives a systemic study and review of blast furnace cooling stave lining materials used in the metallurgical industries based on heat transfer analysis. Additionally, the paper describes a model which will be modeled and implemented using Pro- E modeling software. The model will further be utilized for the analysis of the behavior of lining materials at different loads through heat transfer analysis by finite element method software called ANSYS.

In this study two different types of bricks like silicon carbide brick and high alumina bricks will be taken for the lining material of the blast furnace cooling stave as well as two different types of skull is considered, in which the first is having negligible thickness and the other one is having certain thickness, (thickness in mm is considered), so, with these two skulls, the heat transfer analysis will be done at different temperatures (loads) from 773k to 1573k in order to compare which lining will give better results than the other.

***Index Terms*: Blast furnace, Cooling Stave, Heat transfer analysis, Thermal Stress field.**

I. INTRODUCTION

A. *Overview*

The blast furnace is fundamentally a vertical shaft varying in height from 24 to 33 meters with a diameter at the hearth of about 8.5 m. It is the most widely used iron making process. The total volume is more than 1400 cubic meters. The blast furnace has charging arrangements at the top and a means of running off the pig iron and slag at the bottom. Air is blown in near the bottom of the furnace, and this increases the speed of combustion and maintains the necessary higher temperature. The schematic diagram of the blast furnace is shown below in Figure 1.1.

Blast furnace performance increased dramatically over the past 15 years due to the higher competitiveness of the global steel market and the availability of the less costly alternatives to steel. Productivity and daily output must be high and downtime must be minimal. The operating and maintenance cost must be as low as possible without influencing the life of the furnace which is extended upto 15 years nowadays. Due to this the number of blast furnaces in the world is decreasing year by year although the cumulative output of all the furnaces in operation remains relatively stable.

Despite the increase in productivity worldwide, which inevitably means greater stress on the furnace itself, its life also needs to be increased to ensure a higher return on investment.

B. *Variables influencing blast furnace life*

Furnace cooling technology is becoming increasingly important for the metallurgical industry as several trends in metallurgy pose more severe demands on the smelting vessels. The first trend is the evolution towards higher process intensities. This includes both an increase in process temperatures to improve thermodynamics of the reactions and an increase of the bath agitation to improve reaction kinetics and has the advantage that higher production rates can be achieved and smaller smelting vessels with reduced capital and operating cost may be used. A second trend in metallurgical industry is the evolution towards more complex and corrosive metallurgical phases, which is largely driven by the need for new and more efficient processes to produce and recycle materials.

The trends towards higher process intensities and more complex metallurgical phases mostly result, in faster degradation of the furnace. Typically the degradation mechanisms of traditional furnace walls can be classified as chemical, thermal, and mechanical stresses. These can appear as a single stress factor; however, combinations of these stresses occur and affect the furnace lining. The most important chemo-thermal wear mechanisms of traditional furnace linings are corrosion by slag, metallic/slag infiltration, metal oxide/carbon bursting, redox reactions, sulphate attack and hydration. An example of this is the acidic, fayalitic slag in the copper industry that can infiltrate into the open pores of the bricks due to its low viscosity. The depth of the infiltration is also a function of wettability of the refractory oxides, surface tension and temperature of the infiltrate, temperature gradient of the brickwork, and size and distribution of the pores. As a result a degeneration (softening) of the brick's microstructure occurs due to chemical attack [1, 2].

With higher productivity, the demands placed on the blast furnaces lining/cooling system are considerable. The life of a blast furnace is usually ended when the refractory lining combined with the cooling system is beyond the point of repair and the furnace needs to be relined. Therefore, it is of utmost importance to minimize the wear rate of the lining/cooling system.

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The wear rate of the lining cooling system can be minimized by altering three variables, each during a different phase starting at the deigning phase. The first is the quality of the lining/cooling system design which can be altered only during the design phases before the actual reline starts. The second is the quality of the installation of the lining/cooling system which can only be altered during the reline. The third is the operation of the blast furnace which can be altered during the campaign life that commences with startup after the reline.

According to Tijhuis et al [3], the least important of the above is the installation quality which leaves the quality of lining/cooling system design and operation of the blast furnace. In particular the operation of the blast furnace is of paramount importance to ensure long furnace campaigns.

Lately, much progress has been made in improving raw materials quality as well as distribution of the burden inside the furnace. A modern furnace will be operated today in such a way that the process is as stable as possible. This includes the burden quality, burden distribution, continuous tapping, and minimum number of stops to do maintenance (shutdowns) and so on. Deviation from what could be described as "normal operation" occurs all the time and can never be prevented. First of all, during stable or normal operation, minor fluctuations in pressure drop and heat flux to the wall occur all the time. Obviously the design of the furnace must be able to cope up with this.

Extreme operating conditions or extreme deviations however are more important to keep in mind in the design stages of the cooling/lining system. For example, different coke quality, problems with distribution, change in burden composition, a long furnace stop, or stops at a too frequent interval, can all have a dramatic impact on the design of the lining/cooling system. In particular, the heat flux level and temperature fluctuations in bosh and lower stack increase with these changes, causing increased lining wear.

As an example it could be seen that many shutdowns are not advantageous for the preservation of the refractory materials and a long campaign life. Wilms et al [4] show in their paper that a long life could be reached if the blast furnace has a mostly continuous operation with fewer shutdowns.

Therefore, the life and performance of a blast furnace is not determined by the normal operation mode, but by the extreme operating conditions the furnace experiences. The lining/cooling system of a blast furnace must be able to cope with the worst deviations one can expect during the campaign. For each and every blast furnace the conditions for which to design a refractory lining and cooling system are different.

C. Development of Blast Furnace Cooling Stave

"Irrespective of the use of so called refractory materials, the best means of maintaining the walls of the blast furnace is with cooling water." These words were spoken by Fritz W Lurman [5], a well known blast furnace man from the time shortly before the turn of century.

The main function of the cooling system is to cool the furnace shell and prevent it from over heating and subsequent burn through. To accomplish this, the cooling system must be able to take up the excess heat generated by the furnace and loaded onto the shell. This heat will lift the shell and lining temperature too high, if the cooling system is not effective in dispelling it.

Cooling Stave:

This invention relates to a cooling installation for metallurgical units, the walls of which are subjected to thermal fluxes of elevated temperature and, more particularly, to the cooling of blast furnaces by means of stave coolers. Modern blast furnaces are increasingly utilized at such velocities and pressure levels that it is important to control the heat fluxes and their transfer, particularly in the zones of the bosh, the body, and the lower, mid, and upper shaft. In particular, in the case of self Supporting units, it is indispensable that the shell not be affected by the temperature level and not be subjected to the variations in temperature which could lower the shell's resistance to the strains to which it is subjected. The heat flux emitted in the different zones of a blast furnace must be collected by a heterogeneous system consisting of a lining, a cooling element, that is, the stave cooler, a shell, such that the cooling element serves the double function of effective cooling of the lining and screening the passage of the flux towards the shell.

Types of cooling stave:-

Smooth Surface Cooling Stave: - stave is of simple structure and good thermal conductivity, the hot face is smooth face with thickness of 70~140mm. It is mainly used in the tuyere and below area as the inner lining of BF hearth cooling.

Common Brick Inlaid Type Cooling Stave:- The hot face of this kind of stave is spacing lined refractory brick, and mainly used in bosh, belly and middle and lower part of stack. Brick inlaid is high alumina brick, silicon carbide brick and etc.

Common Ramming Mass Type Cooling Stave: - The hot face of this kind of stave is spacing lined dove tail with crushing refractory materials inside, and is mainly used in bosh, belly and middle and lower part of stack. Ramming material alumina carbon or silicon carbide brick

Complete Cover Type Brick Inlaid Type Cooling Stave:-The characteristic of cooling stave is hot face (working face) is completely covered by bricks with thin or non lining structure to enlarge the furnace volume. It is mainly used in bosh, belly and middle and lower part of stack

Cooling stave arranged against the internal face of the shell between this latter and the refractory coating fulfill a double function. The staves are made of cast iron, steel, copper elements having a network of tubes in which circulates a cooling fluid, which in the prior art, is water, and which is subjected to a vaporization upon contact with the heat flux which the stave cooler has to be absorbed. The goal of this paper is to review some aspects of this process. The main aim of the study is to analyze the behavior of lining materials at different loads through heat transfer analysis by finite element method software called ANSYS. In this study two different types of bricks like silicon carbide brick and high alumina bricks will be taken for the lining material of the blast furnace cooling stave as well as two different types of skull is considered, in which the first is having negligible thickness and the other one is having certain thickness, (thickness in mm is considered), so, with these two skulls, the heat transfer analysis will be done at different temperatures (loads) from 773k to 1573k in order to compare which lining will give better results than the other.

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II. REVIEW RELATED TO THE WORK

The present section of the paper provides a brief review of blast furnace cooling stave lining materials based on heat transfer analysis. The problems related to the parts of blast furnace like hearth, bosh, tuyere and so on has been formulated in the work of many researchers and various methodologies have been proposed. So far not much of the work has been done in the erosion of the walls of the blast furnace mostly in the region of bosh, hearth etc. After a proper and detailed study of the work of many researchers, it has been observed that, there is a vast scope in the study of the blast furnace cooling stave, because of the reason that a variety of materials are being used for cooling stave like cast iron, steel, copper and many refractory linings. Therefore, the behavior of each and every lining material at different loads and at different temperatures is a very significant basis for the proper study and analysis. The life of the blast furnace greatly depends on the wall of the furnaces i.e. the life of the wall is directly proportional to the life of the blast furnace. Proper and significant calculations on the basis of heat transfer has been done, in the region of the cooling stave such as by changing the thickness of the linings, by changing the velocity of the linings, inter distances of the cooling channel, by changing the radius of the cooling pipes, by changing the thickness of the inlaid bricks and many more. The aforesaid studies have been done on single-single refractory linings such as in silicon carbide or high alumina or graphite lining and so on.

In 2006, Karel Verscheure et al [6] in their work discussed a reliable furnace cooling technology which is a domain of increasing concern to the pyrometallurgical industry as it can significantly increase process intensities, productivity and campaign times of furnaces. Their work gives a review of different cooling designs used in the ferrous, non-ferrous and alloying industries. Additionally, their work systematically reviewed aspects of materials selection, manufacturing, installation, water quality and furnace monitoring when using water cooled refractory's.

In 2006, Wu Lijun et al [7] in their work proposed (and implemented) a three dimensional model for heat transfer calculations of a blast furnace cooling stave by utilizing different types of cooling pipes. Initially they used circular pipes, followed by elliptical tube and oblate tube. Based on these geometries proper study and analysis has been done. The finite element method software ANSYS had been used for the calculation of temperature and thermal stress of stave on different types of tubes. In elliptical tube, as the value of (a/b) was increased, the maximum temperature as well as the thermal stress of hot face decreases and hence a conclusion is made that the maximum temperature and thermal stress of the hot surface is not high when cooling pipe is replaced by elliptical tube. In case of oblate tube as the value of (a/b) was increased, the hot face temperature got decreased and authors drawn the conclusion that the maximum temperature is unstable in oblate tube due to which the oblate tube could not be considered as an ideal cooling channel.

In 2007, Qian et al [8] in their work stated that cast steel blast furnace (BF) cooling staves are widely used in the Chinese steel industry. The authors developed a heat transfer mathematical model of a BF cast steel cooling stave verified by thermal state experiments. They carried out the calculation of a cooling stave working under steady state based on the model and discussed the effects of two factors- *thickness of scale on the cooling water pipes* and *gas clearance between the pipes and main body*, which are difficult for experimental measurement but determined mathematically, on the temperature field of the stave body. They on the basis of their results indicated that much importance should be attached to the two factors during manufacturing of cooling staves as they highly influence cooling capability of cooling stave and hence BF operation.

In the year 2007, Wu Lijun et al [9] in their work presented a three dimensional mathematical model of temperature of blast furnace cooling stave. They proposed some parameters based on which the heat transfer analysis has been done. They have used modeling package Catia (v3) as well as ANSYS (version 10.0) for their analysis work. The authors had solved conduction as well as convection heat transfer rate using different equations and have used the thermal values in the stress calculations using CFA and hence on the basis of the values of temperature and stresses, a conclusion has been made that cooling water velocity has an influence on the maximum temperature of the hot face but no influence on the thermal stress of the stave.

In 2008, Wu Lijun et al [10], proposed a three dimensional mathematical model of temperature and thermal stress field of the blast furnace stave. In their work, the effect of radiation heat transmitted from solid materials (coke and ore) to inner surface of the stave has been neglected. In this, heat transfer analysis is made of the effect of the coating layer on the external surface of the cooling water pipe as well as the gas clearance on the maximum temperature and thermal stress of the stave hot surface. They derived a conclusion that, there is an effect of cooling water scale on stave, i.e. the maximum temperature and the thermal stress of the stave hot surface increases with the increase of the thickness of the water scale.

In order to study the effect of gas temperature variation on cooling stave, in 2010, XIE Ning-qiang and CHENG Shu-sen [11] in their work, analyzed temperature, stress and displacement distributions of cooling stave respectively when gas temperature inside- blast furnace increases from 1000 to 1600 'C. The conclusions made by the authors are that the temperature near the top and bottom sides is higher than in the other regions and maximum values are on the hot sides. One more conclusion drawn by the authors in their work is that the stress intensity on cold surface is mainly affected by water pipes and much higher on the hot side. The crack formation results were also obtained by them in their work.

The gradual progress in the area of blast furnace cooling stave has been surveyed in this section of the thesis. The issues for the further research in this area have been also investigated and specified in the subsequent sections of the present paper.

III. PROBLEM FORMULATION

A. *Introduction*

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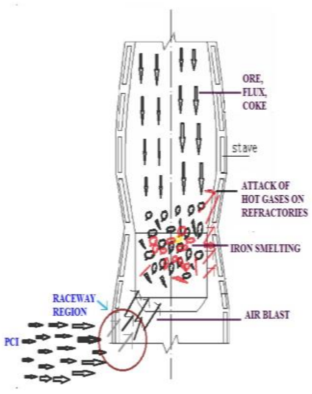

Figure 1 Introduction to the problem.

The biggest heat load of a blast furnace is concentrated within the lower stave region of a blast furnace with intensified smelting. Cooling staves is one of the most important reasons that bring in major overhaul of a blast furnace. Therefore, cooling stave life is a key parameter for the life of a blast furnace.

Figure 1 shows the smelting process and the arrows shows the state after smelting process. The body of the blast furnace is built up of steel and the cooling stave is built using cast steel. Cast steel has been preferred because life of a cast iron cooling stave is too short and copper cooling staves capital cost is too high. Some advantages of using cast steel are: high specific elongation, tensile strength, melting temperature, thermal conductivity.

B. Process

This section gives a brief description about the actual process inside the blast furnace. Initially a huge blast of fuel gases comes from the tuyere. From the lance in the tuyere, pulverized coal injection (PCI) coal is injected and from the bustle pipe air `is passed, the combustion takes place in the raceway region as shown in the Figure 2.1, after this a huge blast proceeds towards the bosh region where the coke, flux, ore comes from the top (bell valve region) region. The process of smelting takes place in the bosh region (smelting region). After this smelting process, molten iron goes to the hearth portion and the combustion gases would then attack the wall of the blast furnace. Since slag has low density it would come over the hearth portion and hence will settle down or would form a layer over the surface of the wall of the furnace of the blast furnace.

Cooling staves are placed along the periphery of the blast furnace wall. So, each cooling stave will face different loads such as the cooling stave placed near to the bell valve (top) would face low temperature as compared to the stave which is placed near to the smelting region. Hence, each stave is considered separately because the biggest heat load of a blast furnace is concentrated within the lower stave region because of the smelting process.

In this paper, for the proper study and analysis of blast furnace cooling stave, the cooling stave at 5 different loads has been proposed to be considered from 773k to 1573k.

The water temperature is taken as 303k, and the parameters related to the modeling and the analysis will be discussed in the simulation and analysis part of our work.

C. Blast Furnace Cooling stave Model

The above stated problem has to be modeled by constructing a model that has been modeled in the modeling software, after that the model has to be export in .IGES file. Now, when the model will be imported in the ANSYS package, the material selection, assumptions and boundary condition will be provided for proper implementation.

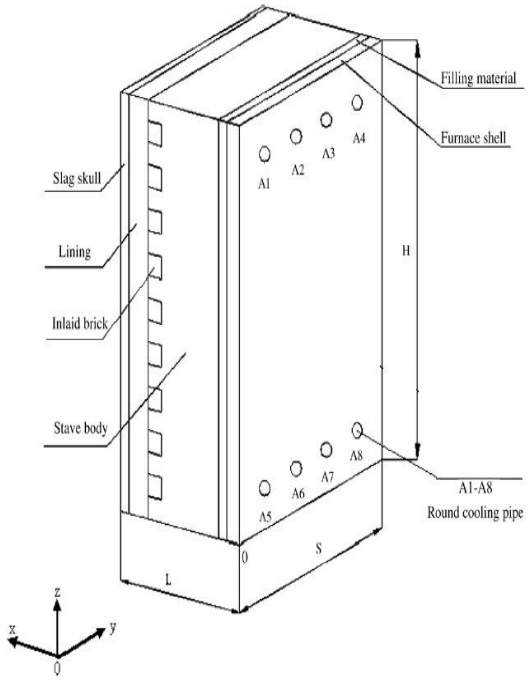

Figure 2 Cooling Stave with linings.

In the above Figure 2 along with the cooling stave, some linings are present like refractory lining which faces the hot gases, after that it is faced by inlaid bricks followed by filling material and furnace shell. Few holes as shown in the figure, represent the cooling pipes, hence, four cooling pipes are connected, and in the above modeling we had used nine inlaid bricks. The above model has to be constructed in the Pro-E wild fire (5.0) modeling software.

D. Proposed Dimension Parameters

Table 1.1 Design Parameters (Dimensions)

Part	Length	Width	Height
Furnace shell	10	718	1400
Filling Material	8	718	1400
Stave body	180	718	1400
Inlaid bricks	70	718	70
Lining	100	718	1400
Slag skull	42	718	1400

Table 1.2 Design Parameters (Dimensions)

Part	Diameter (mm)	Length (mm)	Numbers used
Cooling channel (pipe)	50	200	4

Table 1.3 Design Parameters (Dimensions)

Part	Volume (mm x mm x mm)	Numbers used
Inlaid bricks	70 x 718 x 70	9

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Table 1.4 Design Parameters (Dimensions)

Part	Volume (mm x mm x mm)
Blast furnace cooling stave	340 x718 x1400

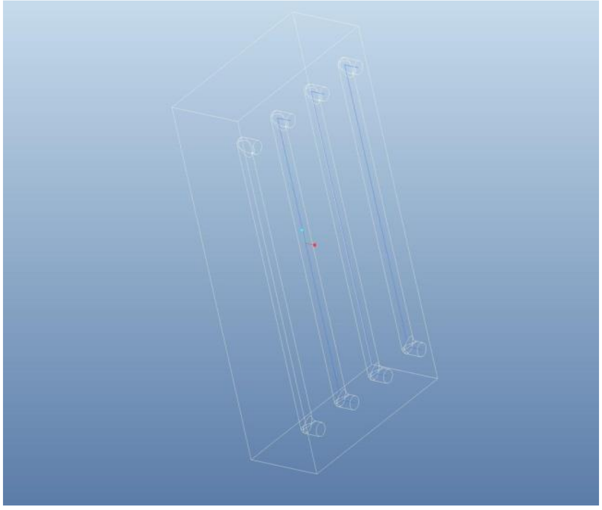

Figure 3.1 Model (Without Skull)

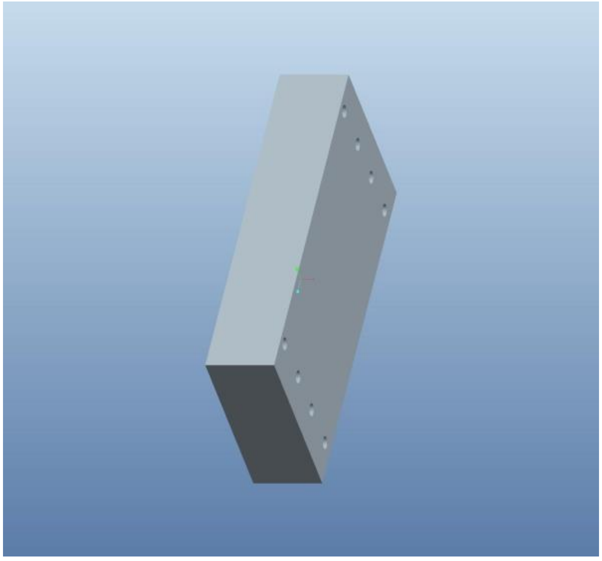

Figure 3.2 Model (Without Skull)

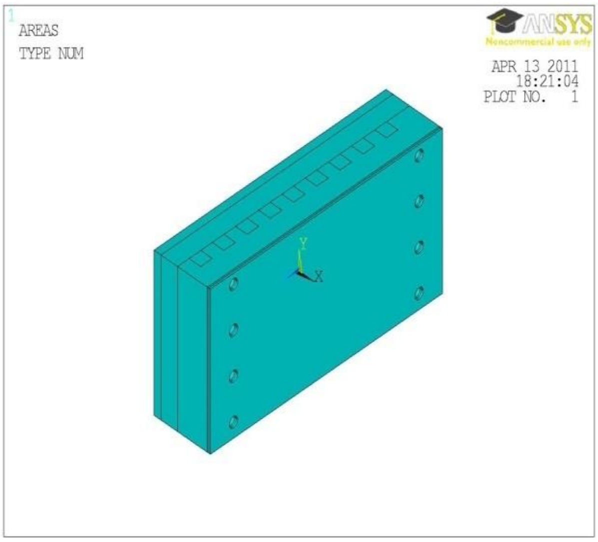

Figure 4 Model (With Skull)

In the present work, the problem has been formulated and initially a model has been made in the modeling software. Further the model has to be exported in .IGES file. For the proper mathematical study and analysis, the model has to be imported in the ANSYS package where the material selection, material properties, further assumptions and hence boundary conditions will be provided for a systematic study and analysis.

The mathematical analysis and solution methodology with relevant partial conclusions and results will be illustrated in the next sections of the present paper.

IV. PROPOSED SOLUTION METHODOLOGY

Our proposed solution methodology involves a proper simulation and analysis of the initial model formed in the above section. Some assumptions will be made in the modeling as well as in analysis part.

In modeling part, the upper edge and lower edge of the stave is fixed; and in the analysis part, the assumptions like steady state conductive heat transfer process, no heat transfer between linings, stave, filling material, furnace shell has to be made.

By this design obtained from Pro-E and analysis from ANSYS, some results in the form of temperature contours will appear over the surface of model. By taking this temperature values from the temperature contour, coupled field analysis will be done for thermal structural calculations to check the bulging in the model as well as to check the failure of the model at higher temperatures (loads) peel stress, shear stress, von mises stress will be calculated, by considering all the values of stress, temperatures, temperature-structural analysis comparison will be done in both the linings.

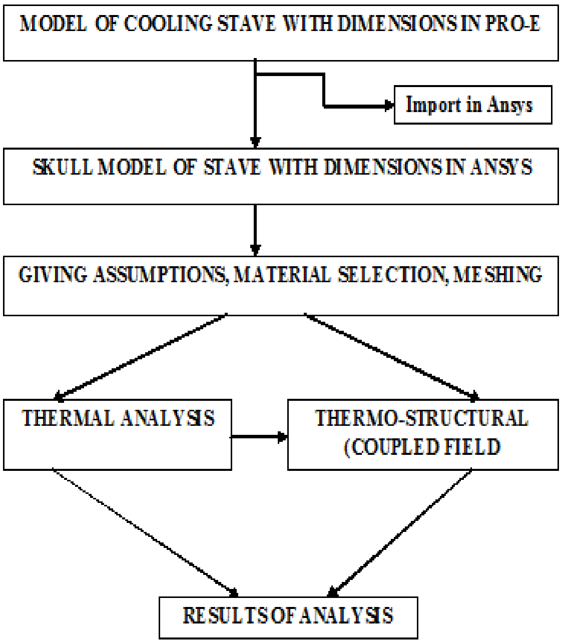

Figure 5 Proposed Flow Chart of the Simulation and Analysis

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Figure 5 shows an initial model that has been modeled and described in the section II of the present paper. It has been made using PRO-E modeling software. After that, the model has to be exported in .IGES file. Now, the instance when the model will be imported in the ANSYS package, the material selection, assumptions, and boundary conditions will be provided. After this, the thermal calculations will be done and then the value of the temperature from the thermal calculations will be used for the calculations of thermal-structural analysis called coupled field analysis.

In the proposed analysis, some stresses like peel stress, shear stress, von- mises stress has to be calculated, and after these calculations, proper results have to be studied and analyzed in the form of profiles, contours and graphs.

The steps for simulation and analysis are summarized as follows:

i. After importing the .IGES file from Pro-E, the model is divided into 5 parts: Filling material, lining, skull, stave and furnace shell.
ii. Now, the first step is the material selection. The material is selected for the linings i.e. for the lining material silicon carbide brick as well as high alumina brick is selected and for the inlaid bricks silicon carbide brick is selected.
iii. After this the material properties will be provided like young's modulus, thermal conductivity, expansion ratio, Poisson ratio and so on. After providing all these values, the process of meshing is done. Meshing is done to get accurate results at each and every node. After doing all these processes, loads will be provided.
iv. The above assumptions and boundary conditions are applied for the thermal calculations as well as for the thermal – structural calculations.
v. Five different loads are applied on the hot surface of cooling stave because the positions of the cooling stave are varying. From top to the bottom, (near the smelting zone) the staves will be placed.
vi. Therefore, the idea is to check the stability of stave at different temperatures.
vii. When combustion will take place, a huge blast having high temperature attacks the wall near to the smelting zone, but as the blast goes to the up side of the blast furnace, its temperature reduces, so that the hot face temperature of top stave (near to bell valve) temperature at that particular combustion will be different as compared to the temperature near to the bosh region.
viii. One modification is done in the model. The upper and the bottom edge of the stave is fixed, i.e. the movement is restricted and the structure is rigid.
ix. The convection between water and water scale (forced convection), conduction of cooling water scale on the inner surface of cooling water pipes and conduction in the steel pies are not considered in this study.

In the present section, a thorough formulation of the solution methodology has been made involving the analysis and simulation of the proposed model, which has been done for the formation and simulation of the stave model. Also, the systematic analysis steps with relevant methodology has been illustrated in the current chapter of the present paper work In order to understand the analysis part, further results has to be illustrated which will be our future work.

V. PROPOSED OUTCOME

After providing the materials properties and the loads, solution will be obtained in the simulation phase. At the end, from the general post processing, the results will be calculated in the form of contour plots and graphs. After calculating the temperature values from the thermal calculation, these values will be reused for the calculation of structural analysis.

The graphical and contour plots of the thermal analysis of with skull model and without skull model of alumina and silicon carbide lining at different loads will be obtained for the cooling stave. Various contour plots and graphical plots related to displacement, von-misses, peel stress, shear stress in the hot face of the stave and the contour plots will be determined across all the four planes (i.e. linings) of the stave and would be plotted and these contour plots will be analyzed critically and discussed in our future work.

Thus, the proposed outcome involves a thorough discussion about the model, and the values and the advantages as well as drawbacks of both the linings (alumina and silicon carbide) and some effects of using those linings in any blast furnace at different load conditions would be clearly stated and discussed based on the results of the simulation and analysis. In the next section of the thesis, the summary and conclusions of the proposed problem and solution methodology of blast furnace cooling stave is thoroughly discussed.

VI. CONCLUSION AND FURTHER WORK

This section of the thesis incorporates the overall conclusions of the present work. In modeling and proposed analysis methodology of the cooling stave, the main element is the tool by which simulation is to be done. So, Pro-E software is used for the modeling and ANSYS is used for analysis.

The results will be achieved based on some parameters, assumptions, and boundary conditions. These all values will be taken from plants, journals, books etc.

Thus, the main aim of this study is to propose a methodology for analysis and comparison of the linings in different stated conditions.

The main aim of the study is to analyze the behavior of lining material at different loads through heat transfer analysis by finite element method software called ANSYS.

In this study, two different types of bricks like silicon carbide brick and high alumina bricks is considered for the lining material of the blast furnace cooling stave as well as two different types of skull is considered, in which first is having negligible (without) thickness and the other one is having certain thickness in mm is consider. So, with these two skulls, the heat transfer analysis will be done at different temperatures (loads) from 773k to 1573k in order to compare which lining will give the better results than the other and hence the simulation and the above mentioned analysis is the further scope of our work.

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