International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 1 Issue 9, November- 2012

A Comprehensive Modeling And Analysis Of Blast Furnace Cooling Stave Based On Thermal Stress And Heat Transfer Analysis.

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***Abstract*— In this paper, the three dimensional mathematical model of heat transfer and thermal stress field of a steel cooling stave in a blast furnace has been modeled. Kinds of the parameters optimization of cast steel cooling stave in a blast furnace are proposed based on the heat transfer analysis. The temperature and thermal stress field of cooling stave have been calculated by using finite element method software ANSYS (13.0).**

In this analysis, two different types of lining materials are considered (Silicon carbide brick and high alumina brick). These lining materials are used at different loads, (gas temperature) from 773k to 1573k, as well as stave with skull and without skull are considered at this gas temperature.

The results indicate that the maximum temperature and thermal stress of hot face is highest in silicon carbide brick and lowest in high alumina brick, also, silicon carbide brick can withstand various circumstances which affects the life of the cooling stave as well as the life of the blast furnace.. Some more stresses have been calculated such as peel stress, von - mises stress and so on. Therefore, the suitable lining for blast furnace cooling stave is silicon carbide brick.

***Index Terms*— Blast furnace, Heat transfer analysis, Steel cooling Stave, Thermal Stress field.**

I. INTRODUCTION

A. Overview

The biggest heat load of a blast furnace is concentrated within the lower stave region of a blast furnace with intensified smelting. It has been reported that the average service life of the lining brick in this zone is shorter than in other region. As indicated by practice, damaged cooling staves is one of the most important reasons that brings in major overhaul or medium repair of a blast furnace. Therefore, cooling stave life is the key parameter for prolonging campaign life of a blast furnace. Now, ductile cast iron cooling stave cannot meet the need of campaign life well, and the capital cost of a copper stave is too high. There has been a lot of attention for a steel-cooling stave with high specific elongation, tensile strength, melting temperature, thermal shock properties and thermal conductivity.

For a long time, the design for the parameters of a ductile cast iron cooling stave were obtained by the investigation of the stave erosion or empirical analysis. The design parameters of steel cooling stave were based on rules for those of a ductile cast iron cooling stave. Obviously, it is not a scientific method. Today, with heat transfer calculations applying to the cooling stave of a blast furnace, the computational modeling of cooling stave has been greatly advanced.

There are many mathematical models describing the heat transfer process of a cooling stave. Steiger et al. [1] developed the heat transfer model to predict the temperature field of copper cooling plate and lining. Wang et al. [2] simulated a three-dimensional heat transfer to describe the temperature field in the wall of the lower stack region of a blast furnace. Some researchers [3–9] in China have done some numerical simulations to calculate the temperature field of a cooling stave. However, these models are not applied to steel cooling staves, just copper or cast iron cooling staves, and only the temperature field has been considered. Thermal stress field were not calculated and the temperature for optimization cooling stave was not basically concerned. Therefore, these calculation results are unlikely to satisfactorily describe the damage of cooling stave. The damage is mainly caused by thermal shock due to thermal stress changes within the cooling stave.

This paper describes a three-dimensional mathematical model of heat transfer and thermal stress fields for blast furnace steel cooling stave and lining. Kinds of the parameters optimization of cast steel cooling stave in a blast furnace are proposed based on the heat transfer analysis. The temperature and thermal stress field of cooling stave have been calculated by using finite element method software ANSYS (13.0).

B. Objective

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

In this analysis, two different types of lining materials are considered (Silicon carbide brick and high alumina brick). These lining materials are used at different loads (gas temperature) from 773k to 1573k, as well as cooling stave with skull and without skull are considered, in which the first skull is having negligible (without) 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 the better result than the other.

Some assumptions will be taken in the modeling as well as in the analysis part. In modeling phase, the upper edge and lower edge of the cooling stave is fixed; and in the analysis phase the assumptions like steady state conductive heat transfer process, no heat transfer between linings, stave, filling material, furnace shell are considered.

By this design from Pro-E and analysis from ANSYS, some results in the form of temperature contours appear over the surface of model. By taking this temperature values from the

Manuscript received on November, 2012

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temperature contours, coupled field analysis is done for thermal structural calculations to check he 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 is calculated, by considering all the values of stress and temperatures, and a comparison of the temperature-structural analysis comparison will be done in both the linings.

C. Packages

The above stated analysis is done by two different types of software. First software is a modeling software **Pro-E**, in which a model of cooling stave is made and the other software is finite element method software called as **ANSYS**, which is used to do the analysis or the calculations. In this, material selection, material properties, meshing, thermal, thermal-structure (coupled field analysis), stress calculations are done.

Pro-E (modeling software):-

This is a software use to create complex designs with great precision. The design intent of any three-dimensional (3D) model or an assembly is defined by its specification and its use. In this, each step of designing is completed in a different module. Some steps are:

- Sketching
- Converting sketching into parts.
- Assembly of different parts
- Drafting
- Manufacturing

ANSYS (analysis software):-

It is a finite element analysis (FEA) software package. It uses preprocessor software engine to create geometry, in its preprocessing phase. Then it uses a solution routine to apply loads to the meshed geometry, in its solution phase. Finally it outputs desired results in its post processing phase.

General processes/phases in ANSYS:-

- Preprocessing phase
- Solution phase
- Post processing phase

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 [10], 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 overheating 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.

The paper has been organized in three sections. In Section II (Problem Formulation and Solution Methodology), theoretical discussion on the present work has been made thoroughly. To start with the discussion, a model has been formed for the proper study and analysis, of the cooling techniques used for cooling blast furnaces. In Section III (Simulation and Analysis), the modeling has been done and proper simulation has been done with considerable and experimental results and analysis. In Section IV (Results and Discussions),the results of the present study and analysis has been illustrated and discussed.

II. Problem Formulation And Solution Methodology

A. Introduction

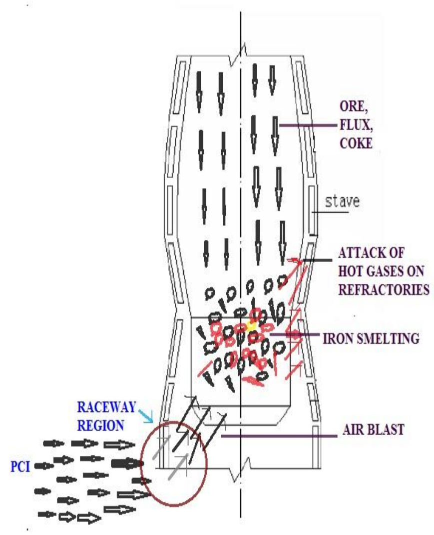


Figure 1 Introduction to the problem.

As already stated in our previous study paper work [11], 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.

As already discussed in our previous paper work [11], 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.

B. Blast Furnace Cooling stave Model

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

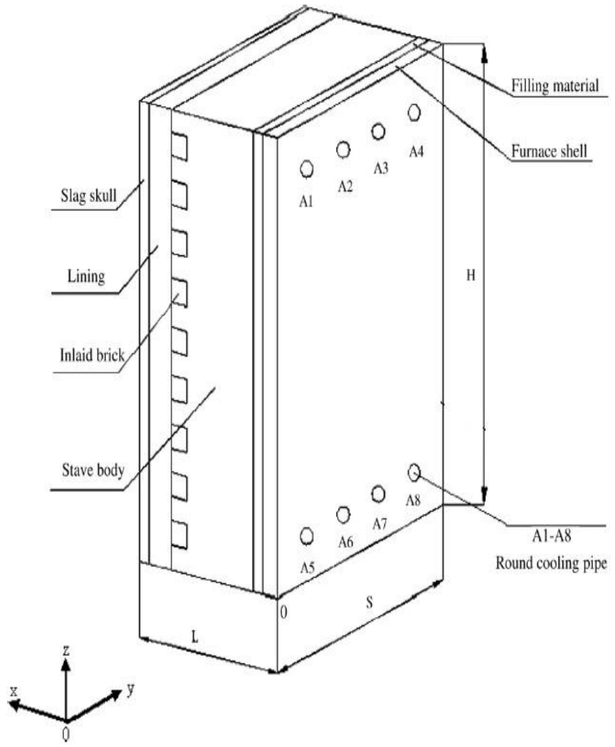


Figure 2 Cooling Stave with linings.

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 been constructed in the Pro-E wild fire (5.0) modeling software by using our **proposed dimension parameters** [11].

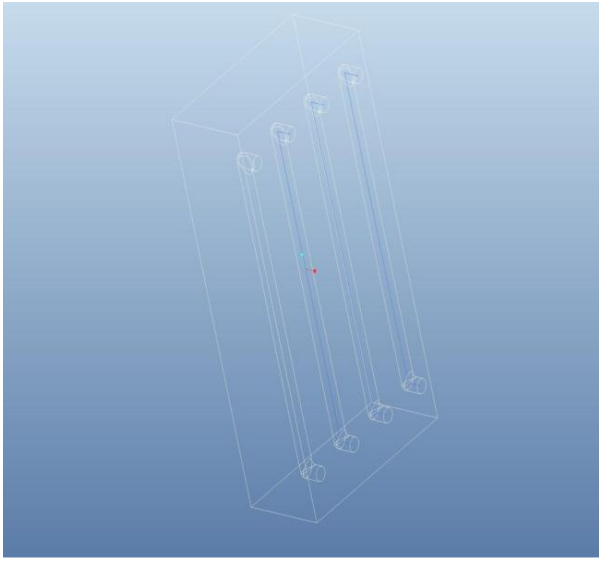


Figure 3.1 Model (Without Skull)

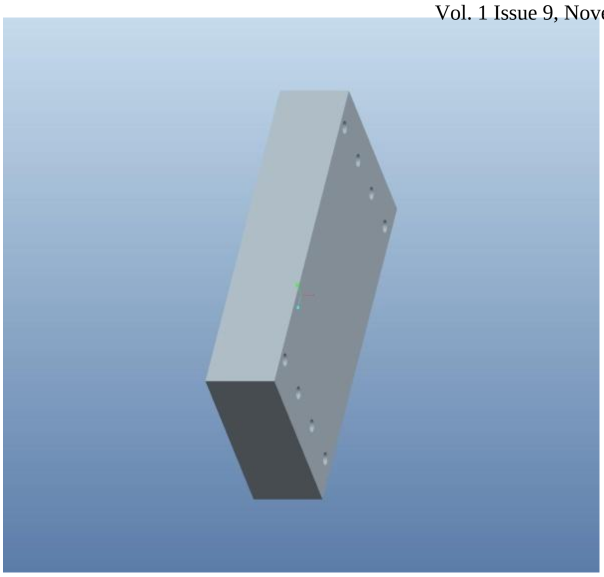


Figure 3.2 Model (Without Skull)

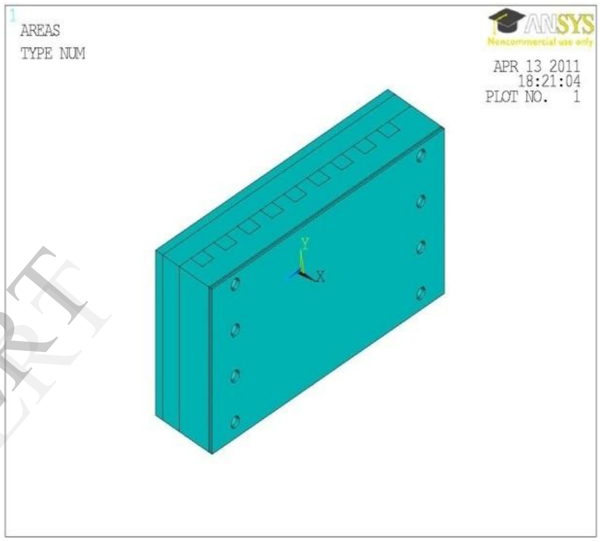


Figure 4 Model (With Skull)

In the present work, the already stated problem in our previous work [11] has been re stated and initially the model which had been made in the modeling software shown in our previous paper [11] is depicted again for proper understanding.

Now, the model has been exported in .IGES file. For the proper mathematical study and analysis, the model has been imported in the ANSYS package, where the material selection, material properties, further assumptions and hence boundary conditions has been provided for a systematic study and analysis.

Our solution methodology had already been stated in our previous work and hence now we present the model which will be used for simulation and analysis and the model which will be used for thermal-structural analysis.

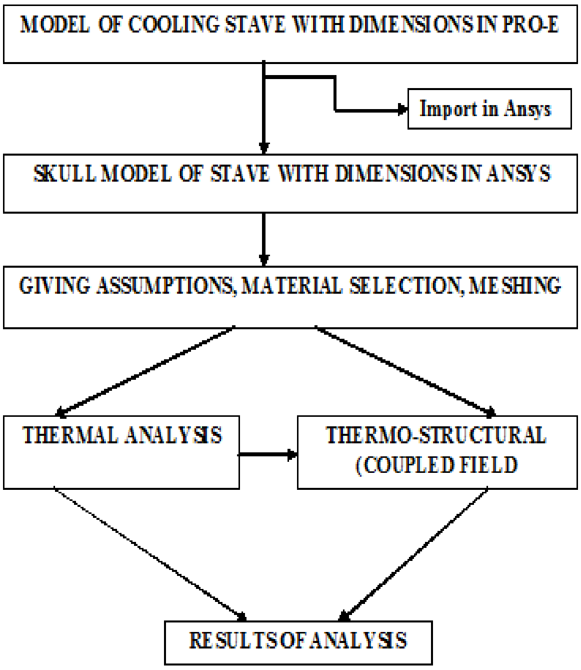


Figure 5 Flow Chart of Simulation and Analysis

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 been exported in .IGES file. Now, the instance when the model has been imported in the ANSYS package, the material selection, assumptions, and boundary conditions has been provided. After this, the thermal calculations have been done and then the value of the temperature from the thermal calculations has been used for the calculations of thermal-structural analysis called **coupled field analysis**. The model used for thermal-structural analysis is depicted below:

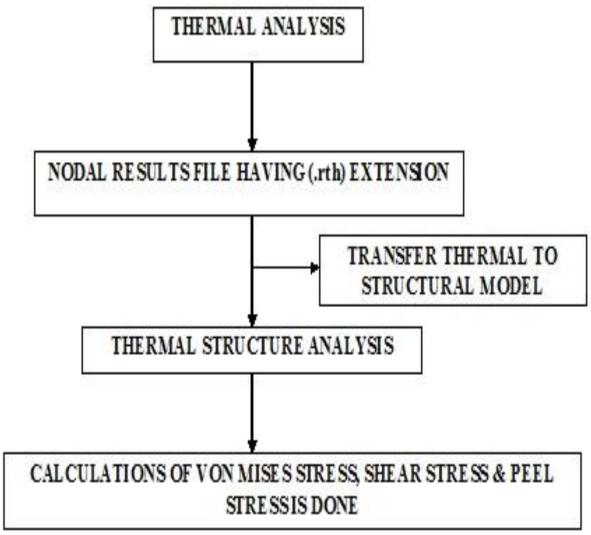


Figure 6 Flow Chart of the thermal-structural analysis

As shown in figure 6, thermal-structural analysis is basically an indirect process; in this the values are directly taken from the thermal calculations. After taking the temperature values, the first step for the structural calculation is to define the properties and the loads. For that some node points has to be defined. After defining the nodal values, temperature is applied on those nodal points as well as load is applied on that particular face. After this, the last process is to obtain the result, which is accomplished by post processing. Hence, the result has to be taken in the form of contours and graphs of peel stress, von mises stress and shear stress.

Von mises stress is basically in an elastic body that is subjected to a system of loads in 3-dimensions, hence, a complex 3 dimensional system of stresses is developed .That is, at any point within the body there are stresses acting in different directions, and the direction and magnitude of stresses changes from point to point.

The Von Mises criterion is a formula for calculating whether the stress combination at a given point will cause failure.

There are three "Principal Stresses" that can be calculated at any point, acting in the x, y, and z directions. (The x, y, and z directions are the "principal axes" for the point and their orientation changes from point to point, but that is a technical issue.)

Von Mises found that, even though none of the principal stresses exceeds the yield stress of the material, it is possible for yielding to result from the combination of stresses.

The Von Mises criterion is a formula for combining these 3 stresses into an equivalent stress, which is then compared to the yield stress of the material.

(The yield stress is a known property of the material, and is usually considered to be the failure stress.)

The equivalent stress is often called the "Von Mises Stress" as a shorthand description. It is not really a stress, but a number that is used as an index. If the "Von Mises Stress" exceeds the yield stress, then the material is considered to be at the failure condition.

III. Simulation And Analysis

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

As stated earlier, in the analysis part of the work, the material selection, material properties, assumptions, and boundary conditions will be provided. These are discussed in details as follows:

1. Material Selection

Table 1.1 Material selection

Part	Material
Lining	Case 1 :- high alumina bricks Case 2 :- silicon carbide bricks
Stave body	Cast steel
Inlaid bricks	Silicon carbide

2. Material Properties

Table 2.1 Material properties

Properties Part	Density (Kg/m^3)	Thermal Conditions (w/m °c)	C_p (J/Kg °c)	Young's Modulus (P_a)	Poisson Ratio	Coeff. of lin. Exp. (/°C)
Furnace shell	7840	52.2-.25t	465	1.7x10^{11}	.3	1.06x10^{-5}
Filling material	330	.35	876	2.1x10^{10}	.1	4.7 x 10^{-6}
Stave body	7800	52.2-.25t	500	1.7x10^{11}	.3	1.06x10^{-5}
Inlaid bricks	2400	21-.009t	963 +.14 7t	2.1x10^{10}	.1	4.7 x 10^{-6}
Slag skull	2000	1.2	983	2.1x10^{10}	.1	4.7 x 10^{-6}
Lining material (alumina)	2750	2.09+.002t	131 0.4	1.65	.25	7.8x10^{-6}
Lining material (SIC)	2400	21-.009t	963 +.14 7t	2.1x10^{10}	.1	4.7 x 10^{-6}

3. Assumptions

- Case 1:- formation of skull is considered.
- Case 2:-formation of skull is not considered.
- Steady state conductive heat transfer process.
- Heat transfer between lining, stave, filling material, furnace shell is not considered.
- Heat radiation heat transmitted from solid materials (coke and ore) to inner surface of the cooling stave is neglected.

4. Loads and boundary conditions for thermal and structural calculations.

i. Air temperature:- 323k
ii. Water temperature:- 303k
iii. Heat convection coefficient:-
   - Between furnace shell and atmosphere:- 12 W/m^{2}k.
   - Between water and inner sides of the furnace shell:- 8000 W/m^{2}k.
   - Between gas and hot side of the cooling stave:-

Table 4.1 Heat Convection Coefficient between gas and hot side of the cooling stave

Temperature in [k]	Heat conv. Coeff. (h) in [m^{2}k]
1273	232
1473	240
1673	250
1873	260

iv. Loads:

Table 4.2 Load values

Different loads applied on the hot face of cooling stave
773k
973k
1173k
1373k
1573k

Further steps for the analysis part can be summarized as follows [11]:

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.

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

Thermal results:-

Few thermal results for the load 1573 k with skull are as follows:

1. Thermal Contours:-

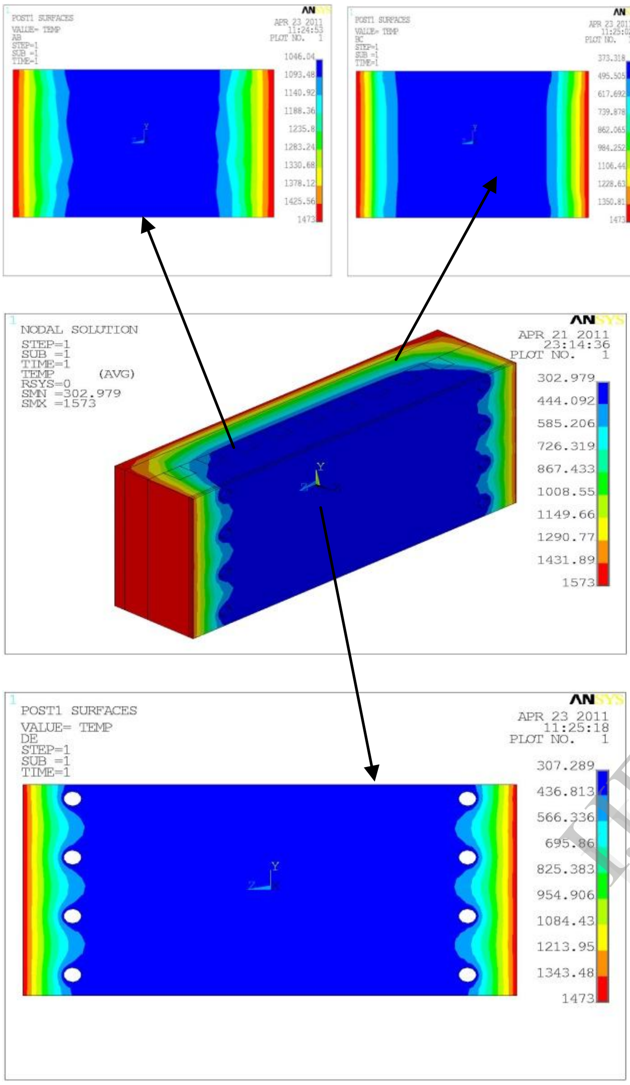
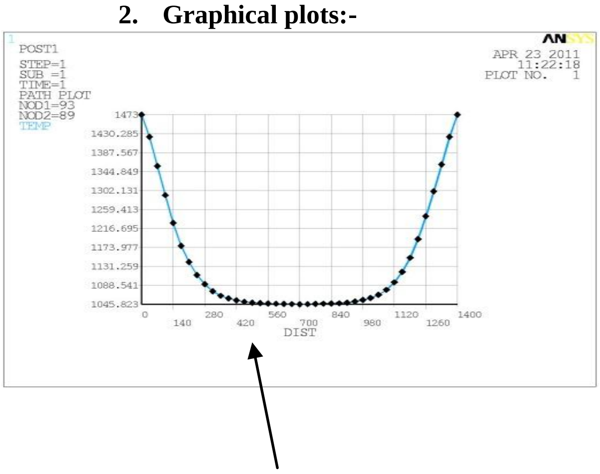


Figure 7 Contour profile at 1573k with skull

2. Graphical plots:-



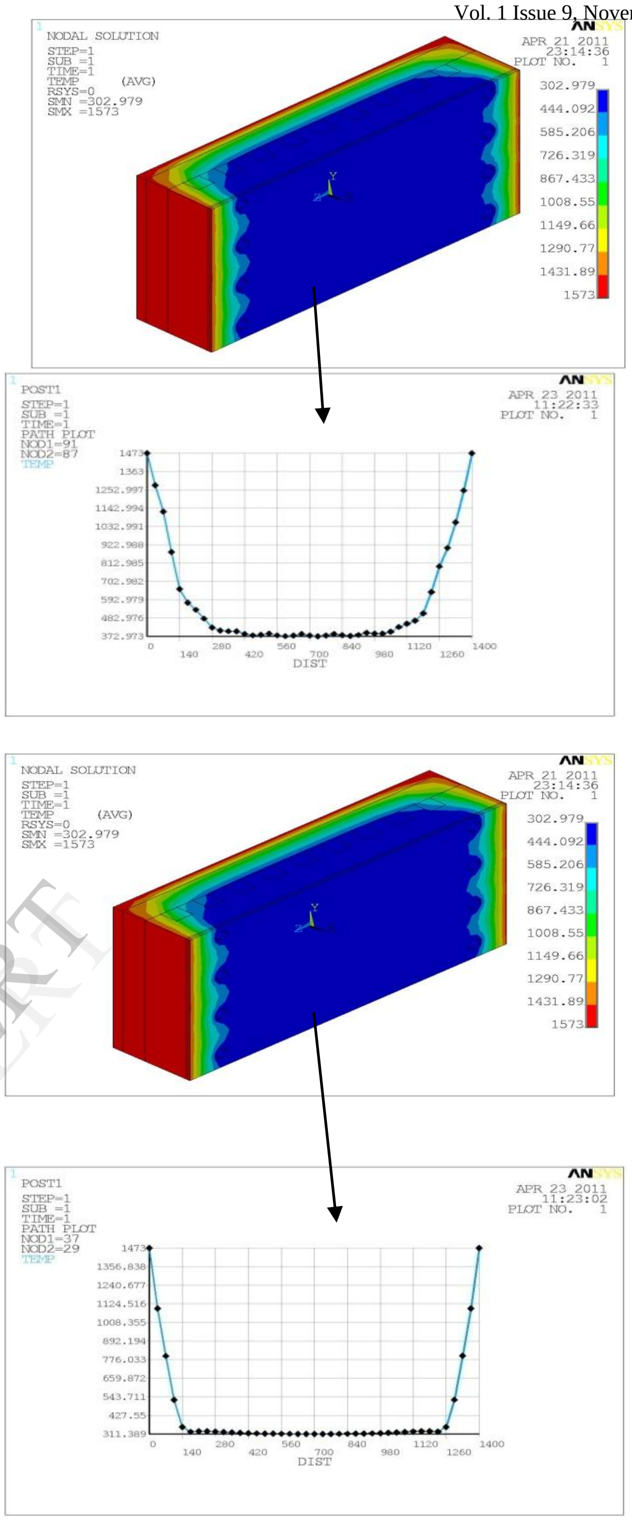
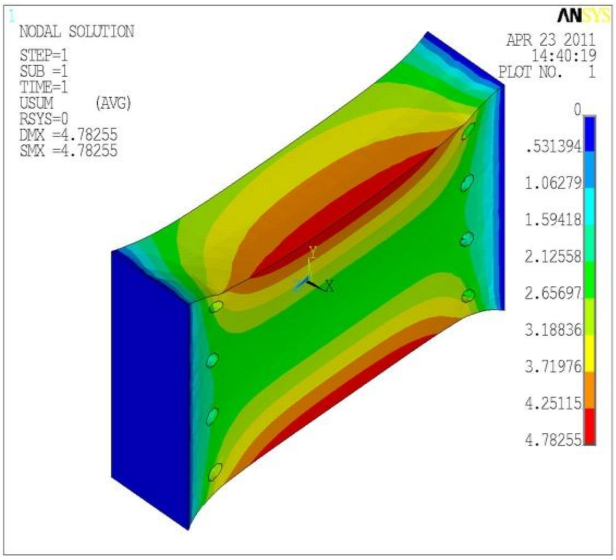


Figure 8 Graphical plot at 1573 k with skull

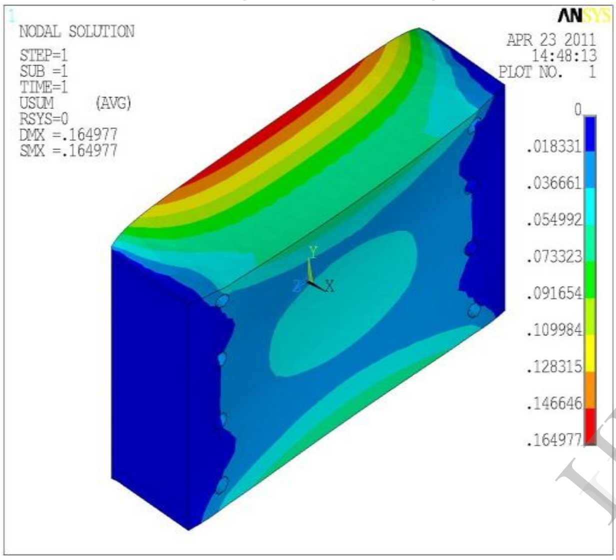
3. Profiles of structural analysis at 1573 k -Displacement contour

ISSN: 2278-0181

Vol. 1 Issue 9, November- 2012



High Alumina Lining



Silicon Carbide Lining

Figure 9 Displacement contours of both linings

In the present section, a thorough analysis has been done for the formation and simulation of the stave model. Also, the systematic analysis with relevant methodology has been illustrated in the current section of the present paper work. In order to understand the analysis part, further results has to be explained, which has been detailed in the next section of the present paper work.

IV. Results And Discussions

The present section of the paper deals with the various graphical and contour plots of the thermal analysis made for the cooling stave (with skull model and without skull model of alumina and silicon carbide lining at different loads). Various contour plots and graphical plots related to displacement, von-misses, peel stress, shear stress in the hot face of the stave and these contour plots are determined across all the four planes (i.e. linings) of the stave and are plotted and these contour plots have been analyzed critically and discussed.

In this study, in the raceway region after the combustion, the hot air goes for the melting of the iron ore, flux and coke. This hot air melts the ore and the molten iron goes to the hearth portion, and the hot air further proceeds to attack the walls of the blast furnace. In the periphery of the blast furnace cooling staves are provided, which keeps the temperature of the walls cool. But at higher temperature attack, the life of the cooling stave decreases, and the life of the blast furnace depends on the life of the cooling stave. Hence, in this study, for the simulation of cooling stave 5 different loads have been taken from 773k to 1573k. Some assumptions and boundary conditions have been taken for the simulation. Initially, a model has been made in the modeling software, after that the file had been imported in the analysis software, and then the material selection had been done. For the refractory lining two different lining materials were considered. The first involved a skull at the hot face and the second involved the case with no skull present at the hotter face of the cooling stave. The first consisted of high alumina brick and the other was silicon carbide brick. Material properties were properly applied in the process and the loads were defined for the thermal analysis. After this, the solution consisted of some results, in the form of profiles, contours and graphs. These results were taken as the reference for the coupled field analysis i.e. thermal-structural analysis. In this, again the loads were applied at the hot face of the stave. From here some results were obtained in the form of contours of peel stress, shear stress and von mises stress. Some graphical plots of von mises stress and peel stress were also obtained from the simulation of the blast furnace. It is not computationally feasible to present the complete results of our work consisting of graphs, plots and contours. Hence, we had discussed them thoroughly in our subsequent paragraphs of this paper.

In the simulation process, the results so far been obtained have been discussed under:-

In case of with skull model:

1. At higher loads, i.e. at 1573k, maximum temperature achieved in case of **alumina** is 1473k and temperature range was found in between 1046k to 1473k, where as in case of **silicon carbide** maximum temperature was found to be close to 1570k and temperature range was in between 54k to 1573k.

From the above observation, we concluded that the maximum temperature in the hot face of **silicon carbide** lining is higher than in **alumina** lining. Some advantages of this are:-

- Melting slag & iron is high in **silicon carbide**.
- Impact of blast furnace charge is high in **silicon carbide**.

2. At 773k, maximum displacement value in **alumina** was 1.65mm and in **silicon carbide** was 1.35mm. At 1573k, maximum displacement value in **alumina** was 5.58 mm and in **silicon carbide** was found to be 5.4mm.

Hence, it clearly reveals that the expansion rate in the alumina lining is more as compared to **silicon carbide** lining.

3. At 1573k, Von Mises stress in **alumina** lining was in the range of 23MPa to 230MPa and in **silicon carbide** it was 24MPa.

From the above statement, it has been concluded that at higher load, the stress value of **alumina** lining crosses the value of steel's ultimate strength value. So, failure will take place at higher load condition.

In case of without skull model:

1. At 773k, maximum temperature in the hot face of cooling stave was found to be 340k in **alumina** lining, but in the case of **silicon carbide** lining the temperature is 483k.
2. At 1573k, maximum temperature in the hot face of cooling stave was found to be 423k in **alumina** lining, but in the case of **silicon carbide** lining, the temperature was 1510k.

Hence, the result concluded was that, the maximum temperature in the hot face of cooling stave was in **silicon carbide** lining. The few advantages of this are:

- Melting slag & iron is high in **silicon carbide**.
- Impact of blast furnace charge is high in **silicon carbide**.

Few more results so obtained are discussed under:

1. At 773k, von mises stress was found in the range of 793MPa to 1.2e4MPa in **alumina** lining but in **silicon carbide** it was 0.1268 to 0.142e9MPa.
2. At 1573k, von mises stress was found in the range of 0.12e10MPa to 0.12e11MPa in **alumina** lining but in **silicon carbide** it was 0.7e5MPa to 0.64e7MPa.
3. Von mises stress of **alumina** is hence, higher than the ultimate stress value of steel, so failure would take place at higher loads.
4. Shear stress value in XY direction at higher load condition was found to be 0.301e9MPa in **alumina** and in **silicon carbide** it was 2.3e5MPa
5. Shear stress value in YZ direction at higher load condition was in the range of -0.2e10MPa to -0.17e10MPa in **alumina** and in **silicon carbide** it was found to be -0.17e7MPa to -0.15e7 MPa.
6. This shows that the shear stress is more in case of **alumina** lining. Hence, the chances of failure in case of **alumina** are more as compared to **silicon carbide** lining.

V. Summary And Conclusion

In the previous section, thorough discussion about the model has been explained, and the values and the advantages as well as drawbacks of both the linings and some effects of using those linings in any blast furnace at different load conditions have been clearly stated and discussed. The above results are only some of the results among all the results so obtained in the simulation part.

In the present section, the summary and conclusion of the simulation of blast furnace cooling stave is thoroughly discussed.

The main aim of this 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 were considered for the lining material of the blast furnace cooling stave as well as two different types of skull were considered, in which first is having negligible (without) thickness and the other one is having certain thickness in mm. So, with these two skulls, the heat transfer analysis has been done at different temperatures (loads) from 773k to 1573k in order to compare which lining would give the better results than the other. This section of the paper incorporates the overall conclusions of the present work. The results and the conclusions which had been achieved are based on some parameters, assumptions, and boundary conditions. These all values have been taken from plants, journals, books etc

From all of the results discussed in our previous section, a final conclusion that has been obtained is, in all the cases silicon carbide lining is better than the alumina lining.

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