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Failure Investigation of Secondary Super Heater using CFD/CAE Technique.

Amit N Parit [1], Tadamalle A. P. [2], and Mrs. V. Ramaswamy [3]
[1,2]Sinhgad College of Engineering, Pune.
[3]Aprameya Associates, Pune.

***Abstract*— The super heater is heart of any boiler system main duty of which is to supply desired amount of steam regularly at rated temperature and pressure. Frequent tube failure in super heaters is found to be crucial problem which is directly related with boiler operation, performance and design parameters. Aim of this paper is to predict possible causes of super heater tube failure. It deals with the failure investigation of secondary super heater tube panel of SA213-T11 grade steel. The primary observations made with visual inspection and then metallurgical investigation has been carried out by microstructure analysis. The temperature distribution on the tube walls of the super heater is analyzed using computer aided engineering tools. From CFD results and metallurgical examination, localized overheating was seen in failed region of super heater tubes. High erosion areas were also seen from computational fluid dynamics. The uneven temperature distribution over the super heater tubes leads to localized overheating, chilling and development of excessive thermal stresses. This analysis is carried out using multiphysics environment which is very useful tool for analysis of many industrial systems like heat exchangers, chillers, cyclones etc.**

***Index Terms*—Super-Heater, Localized Overheating, CFD**

I. INTRODUCTION

Boilers are the key components in power plants which generates steam by efficient burning of available fuels. Now days, fluidized bed combustion technology is proving a better replacement to conventional techniques. The atmospheric fluidized bed and circulating fluidized bed are commonly adopted techniques in the boilers. Fluidized bed technology burns the fuel more efficiently with the help of suspended bed of silica and limestone material. The efficient and trouble-free operation of boiler is very essential to maintain. Reduced performance, repetitive failures in boiler components are common problems related to any type of boiler system. Super heater tube failure is very common issue in boilers. Super heater is basically a heat exchanger in which heat is transferred from furnace gas to the steam. Improper heat transfer between steam and furnace gas leads to problems of localized heating. Uneven heat transfer is a result of non-uniform gas flow or non-uniform steam distribution in super heater. The significant causes of failure in super heaters are localized prolonged heating, creep damage, thermal fatigue, excessive thermal stresses, water and fire side corrosion and erosion etc. General modes of failures observed in the super heaters are wall thinning, reduced thickness, fish-mouth opening type bursting, creep cracks on tube surfaces and puncturing.

Tube failure in the super heater is hazardous enough to shut down whole plant hence it is important to take remedial actions to avoid technical as well as economic losses. Prolonged localized heating which is reported as a root cause of tube failures is a result of flawed operating procedures. Concentrated gas flow pattern over super heater and non-uniform steam distribution leads to overheat localized portion of tubes. Proper distribution of furnace gas over entire super heater tubes and uniform steam flow in each tube is suggested for trouble free operation of super heater. [2] The failure of a few super heater tubes at localized regions in an atmospheric fluidized bed combustor was studied by V.Kain, K. Chandra et al. [1]. High oxidation rates along with high temperature and high gas velocity were noticed as main cause of failure. Creep damage possibility was checked using Larsen-Miller parameter related with primary super-heater tube of a power plant by J. Ahmad, M.M. Rahman et al. [2]. Author noticed that, low melting temperature of ash content in the coal causes heavy clinker formation on the super heater tubes. Microstuctural investigation showed symptoms of localized heating. The common cause of any metallurgical failure of a super-heater tube is due to the tube metal temperature higher than that as originally specified. M.M. Rahman, J. Purbolaksono et al. [3] reported metallurgical aspect of tube failure. Failure analysis on a super alloy Inconel-800 super heater tube is presented by J Ahmad, J. Purbolaksono, L.C. Beng et al. [4] Author investigated excessive hoop stresses are the cause of failure. Failure analysis on the SA213-T12 superheated tube is carried out by visual inspection, hardness measurement and finite element analyses by J. Purbolaksono, J. Ahmad, L.C. Beng et al. [5] Finite element analyses prior to failure were conducted and it was found that, localized short-term overheating of the tube due to localized and concentrated flue gas flow resulted in a failure of the primary super heater tube. A. Husaina and K. Habibb [6] investigated failed steel tube in super heater of the boiler. Material of the tube has suffered from localize heating probably as result of local heat flux impingement caused by gas or burner oil.

CFBC and AFBC boiler plants have been visited to investigate problems related with them. It was noticed that, super heater tube failure is most common issue with both types of boilers. Along with these failures, reduced thermal efficiency and loss of ignition were noticeable problems related with these boilers. Replacement of failed portion of tube or complete replacement of tube pattern are the temporary remedial actions made.

This paper aimed at investigation of repetitive tube failure of secondary super heater (SSH) of an Atmospheric fluidized bed combustion type boiler of 90 TPH capacity. Boiler is coal fired. Silica and limestone are the bed material contents. Boiler is designed to provide steam at rated pressure of 88atm and at about 485-491^{0}C. Longitudinal fish mouth opening burst with reduced thickness at failed portion was seen on super heater tubes. There are no signs of active corrosion and there is no clinker formation on super heater tubes.

II. FURNACE GAS FLOW ANALYSIS OVER THE SUPER HEATER

Computational Fluid Dynamics technique was used to study flow of furnace gas over secondary super heater. Results shows that flow pattern is not uniform. Figure 1 shows secondary super heater block. Design wise it is a bunch of tubes. It has 47 panels each having 6 loops. Each loop has two sections. First five loops has outer diameter of 50.8mm and thickness of 4.06mm. Tube material is SA213-T11. Last loop has thickness of 5mm with same outer diameter.

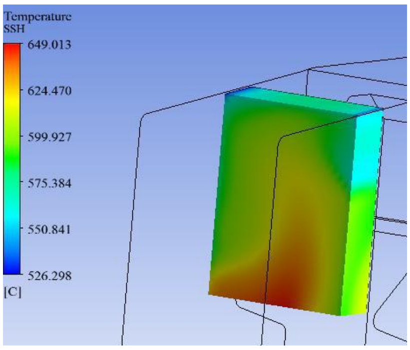

Fig. 1 Temperature on Secondary super heater by CFD.

Three panels from different location are selected for analysis. First, ninth and forty-third panel are selected which have different steam mass flow rate and flue gas distribution over it. Table 1 shows selected panels with selection criterions.

Table 1 Selected panels for analysis

Criteria	Panel No.	Mass Flow Rate
Affected zone (Panels-6-14)	9	0.8433
Higher flow rate (Panels 1-5)	1	0.8932
Lower flow rate (Panels 30-47)	43	0.1647

CFD meshing is carried in Hypermesh-CFD module. For analysis, individual panel is considered. Surface 2D mesh is created to define boundaries of different domain. Solid *tetrahedral* mesh is created with respect to two fluid and one solid volume. Inlet and outlet boundary locations for steam and furnace gas are defined by extracting faces from 3D tetra mesh. Hypermesh provides good mesh quality with useful boundary layer construction on domain boundaries. Figure 2 shows section of CFD mesh carried out in Hypermesh.

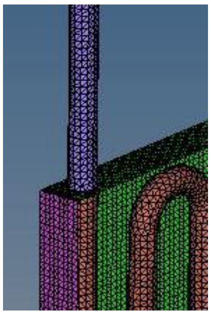

Fig.2 CFD meshing in HyperMesh (section)

Total 4646244 tetrahedron elements were generated. CFD boundary conditions are shown in figure 3. Heat is added into SSH system from front and bottom directions. Three domains namely fluid ‘furnace gas’ domain where gas enters, solid ‘thickness’ domain which is defined with steel metal and fluid ‘steam’ domain which is inside of the tube are defined in CFX. Two *solid-fluid interfaces* are defined between above three domains to carry out heat transfer.

III. COMPUTATIONAL FLOW MODEL

The CFD modeling involves with the numerical solution of the conservation equations. In the most of research, the simulations solution of continuity, mass, momentum and energy equations were carried out by CFD codes. A turbulence model is a computational procedure to close the system of mean flow of mass and momentum equations and solve them so that more or less variety of flow problems can be calculated. There are some well-known turbulence models such as the mixing length, k-ϵ family models, Reynolds stress model etc. In this analysis, due to complicated mathematical work and need to apply model which uses minimum CPU time, standard k-ϵ model is preferred. Transportation equation for k and ϵ by this model are,

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial_{xi}}(\rho u_i k) = \frac{\partial}{\partial_{xi}}\left(\rho \frac{v_{eff}}{\sigma_k}\frac{\partial k}{\partial_{xi}}\right) + \rho(P_{k-\epsilon}) \ldots..1$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial_{xi}}(\rho u_i \epsilon) = \frac{\partial}{\partial_{xi}}\left(\rho \frac{v_{eff}}{\sigma_\epsilon}\frac{\partial k}{\partial_{xi}}\right) + S_\epsilon \ldots..2$$

Where ρ is density and u, v, w are velocity vectors.

With the use of Thermal Energy model, CFX directly computes the static enthalpy. General changes in the enthalpy are also used by solver to calculate thermodynamic properties as temperature. This is an alternate form of energy equation used for low speed flows.

$$\frac{\partial \rho h}{\partial t} + \nabla(\rho v h) = \nabla(\lambda \Delta T) + \nabla V + S_E \ldots..3$$

Where, $\lambda = -2/3\mu$, ∇V is viscous dessipition term. h is enthalpy. Thermal Energy model is used for both, liquids and gases. Radiation model is not defined in this analysis.

IV. HEAT TRANSFER

Steady state conjugate heat transfer analysis is carried out by providing appropriate boundary conditions on furnace gas and steam inlet and outlet. At furnace gas inlet, velocity and Nusselt number are given while static pressure is defined at outlet. Inlet steam mass flow rate is defined while static outlet pressure of 8.9 MPa is given. Analysis is carried out at reference pressure of 101325 Pa. Tube thickness is modeled as solid domain of steel material. Flow of furnace gas over single panel of super heater is shown in figure 6.

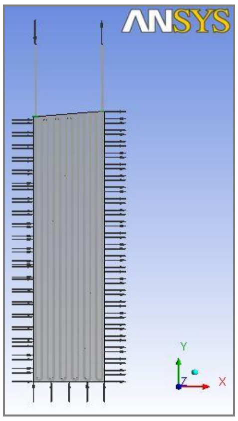

Fig. 3 CFD boundary conditions.

Temperature results are mapped on solid model to carry out steady state thermal analysis. Ansys Workbench multiple system environment is used to carry out this *multiple system* simulation. The material specified is SA213 T-11 alloy steel. Table 2 lists the chemical composition of the material.

Table 2 Chemical composition of SA213 Grade T11 steel.[11]

C	Si	Mn	P,S	Cr	Mo
0.05- 0.15	0.5- 1.0	0.30- 0.60	<0.025	1.0- 1.50	0.44- 0.65

Thermal analysis is carried out to get temperature profile on walls of the tube. To account changes in material properties with respect to temperature, mechanical properties at avarage temperature of 520^{0}C are assumed and listed as below.

Young’s Modulus (MPa): 1.72E5
Yield Strength (MPa): 183
Tensile Strength (MPa): 378.9
Thermal Expansion (mm/mm/^{0}C): 14.16e-6
Poisson's Ratio: 0.33
Density Kg/m$^{3:}$ 7833

97% of nodal temperatures were interpolated on the solid model. Meshing for structural analysis is carried out in Ansys Workbench (V-13.0). Physics preference is mechanical with *solid90* element type. This element supports the thermal properties and conditions. Element size is *20mm*. Total 885980 brick meshed elements with 126189 nodes are generated.

Steady State Thermal analysis is carried out in Ansys Workbench. This analysis gives actual temperatures on tubes. Temperature distribution obtained after thermal analysis is the resultant temperature distribution to which tubes are exposed. Figure 5 shows result of thermal analysis for ninth panel.

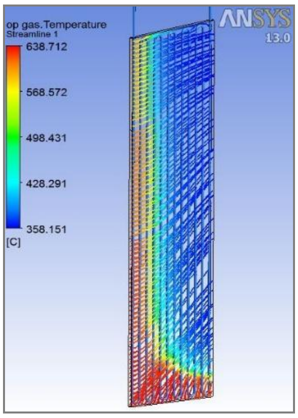

Fig.4 Furnace gas flow over ninth panel of SSH

From figure 5 it is seen that, temperature distribution on ninth panel is is not uniform over the entire panel. Figure 6 shows results of similar analysis for first panel.

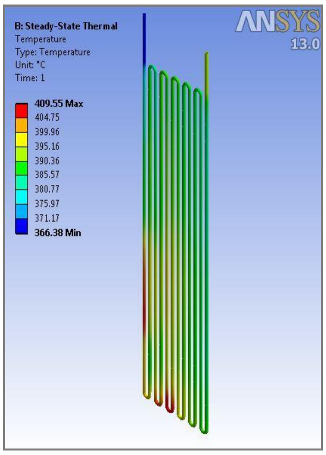

Fig.5 Resultant temperature on ninth panel

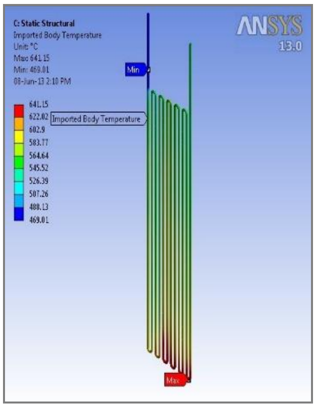

Fig.6 Resultant temperature on first panel

From figure 6 its clear that temperature is less or more uniform over its length.

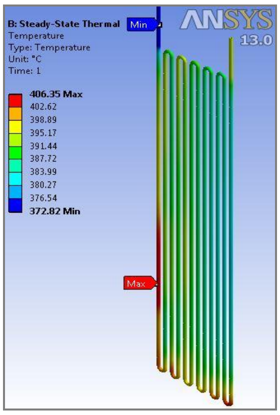

Fig.7 Resultant temperature on first panel.

Figure 7 shows temperature distrinution on 43rd panel. It is seen from figures 5,6 and 7 that, at present operating conditions, temperatures on SSH tubes are not uniform. Bottom bends and first loop are getting overheated.

V. MICROSTRUCTURE

Microstructure is the mirror of material temperature history. Microstructure is studied of failed sample and compaired with that of parent metal. Figure 8 shows failed tube and locations where microstructure has checked.

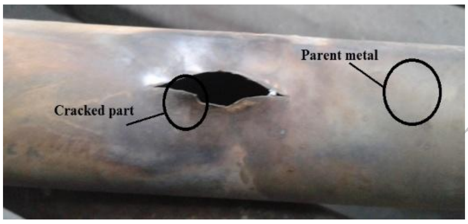

Fig.8 Failed tube showing locations of microstructure examinations.

There are many parameters like grain size, grain structure, spheriodization levels etc. help to define temperature level to which material has exposed. Figure 8 shows microstructural view of both samples. Samples are cut from failed tube and analized. 3% Nital is used as etchant. Figure 9 and 10 shows 200X magnified images of the microstructures.

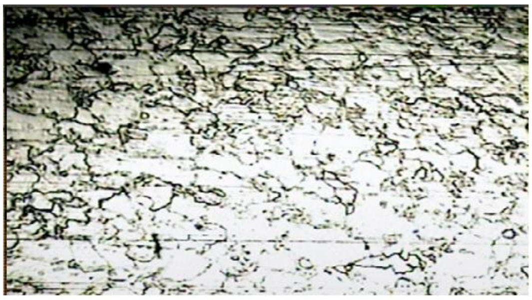

Fig. 9 Microstructure of cracked portion.

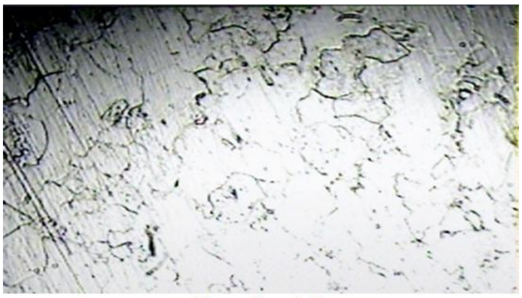

Fig. 10 Microstructure of parent metal tube.

VI. DISCUSSION

Findings from CFD/CAE analysis shows that, some part of SSH is getting heated locally. Bends and first loop tubes are facing much higher temperatures than rest of the tube. This is because, bends are exposed to two heat streams as seen in figure 6. First loop contains steam at comparatively low temperature (about 350^0C) but exposed to highest temperature furnace gas. Hence temperature is not uniform over entire length of the panel. Figure 7 shows resultant temperature on ninth panel. It shows higher temperature regions on first loop and bottom bends. Similarly temperature distribution on first and fortythird panels shows non uniform temperature distribution. This is due to uneven flow distribution of furnace gas over SSH. Steam flow inside the tube is also equally imortant as it acts as heat sink. Flow of the steam in all 47 panels is provieded by single inlet header. In order to take place a proper heat transfer, it is necessary that each panel recieves equal amount of steam. Improper temperature distribution causes non-niform thermal expansions which result in exessive thermal stresses at the bends. A localized overheating is identified in the failed region as evidenced by advance stage of Spherodization as shown in figure 11. J Ahmad et al. [2] stated that, the failure temperature may be indicated by using microstructural evidences. Spherodization of pearlite indicated the evidences of higher temperature. Spherodization in ferrite tube structures would usually commence as the carbon tube metal temperature is around 550-600^0C for longer period of time. As ninth tube is from localized heated portion it shows much higher temperature region on bottom bends. Also at such high temperature allowable stress strength also reduces. Erosion rate also become high at elevated temperature as metal become softer. It can be seen from figure 6 flow pattern of the gas is concentrated over first three bottom bends, in this case these bends are prone to high erosion.

VII. CONCLUSION

Findings from CFD/CAE analysis and microstructure study showed that present failure caused by localized overheating. Non uniform furnace gas pattern over secondary super heater is the root cause of failure. This non uniform flow pattern imparts uneven temperature distribution on tube walls which further leads to and non-uniform thermal expansions over the length. This may lead to excessive thermal stress development. Improvement in flow gas pattern so that SSH will receive equal amount of heat from furnace gas over its entire area.

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