Use of Cold Air Velocity Test (CAVT) to Locate Erosion Prone Zones in Pulverized Coal Fired Utility Boiler

P R Dhamangaonkar, S R Kajale, M R Nandgaonkar, Abhishek Deshmukh, Aditya Deshmukh, Swaroop Thakur

Abstract— **Thermal power plants in India are facing the problem of forced outages due to unexpected boiler tube failures. Fly Ash Erosion (FAE) is one of the prime reasons for these failures. The main cause of this FAE is the localized increase in the velocity of flue gases which in turn increases the velocity of fly ash particles. The rate and extent of FAE depends on various parameters such as particle velocity, angle of impact, particle composition, shape, size & sharpness factor, temperature of particle, surface temperature of tube, population density of particles, coal quality, combustion efficiency, erosive resistance of the tube surface including compositional & temperature variations. Particle velocity is the most important parameter as the rate of erosive loss is proportional to the velocity raised to an exponent that ranges between two and four. Particle velocity is driven by the local flow velocity at any particular boiler location. It is difficult to physically measure velocities of flue gases inside the boiler when it is in operation. However, it is required to know the velocity flow field in various zones so that its effect on the various failure mechanisms can be predicted. The primary tool to combat Fly Ash Erosion is flow modification in conjunction with a cold air velocity test before and after modification. The cold air velocity test is performed to predict the velocities in the respective zones of the boiler. A comprehensive EPRI Guideline has been published which provides a step-by-step procedure of CAVT. In this paper authors have used cold air velocity technique (CAVT) to determine local velocity profiles across various pressure parts. The use of CAVT to identify regions of excessive velocity, followed by the installation of diffusion and distribution screens, may provide utilities with the most optimum solution to the problem. The authors have tried to predict the Cold Air Velocity. The actual geometry of the flue gas path of the 210 MW boiler is created using Pro-E and meshed using GAMBIT is imported in FLUENT for analysis. The inlet and outlet are given pressure boundary conditions. The k-epsilon realizable is used as turbulence model. The results obtained are then compared with the experimental data of CAVT to validate the model. For comparing the results, the points where the actual CAVT is performed are replicated in the simulated model. Cold Air Velocity Test is successfully simulated using FLUENT. The results of the simulation are in good agreement with the experimental results of CAVT with error of order of ±23 %. The sources of errors and their effect on the model in deviation of the conditions from the actual ones are also discussed.**

Index Terms— **Boiler Tube Failure, CAVT, Fly Ash Erosion, Porous Media approach. Utility Boiler,**

I. INTRODUCTION

THERMAL Power Plants contribute about 75% to all India installed capacity of electric power generating stations. Coal continues to be the dominant fuel source for fossil fuel steam generation in the Indian Electric Utility Industry accounting almost 55% of power generated. With ever increasing demand for electricity, it is very necessary for the power plants to generate electricity without forced outages. Boiler Tube Failure is the prime reason of forced outages at coal fired thermal power plants. The severe service condition in coal fired thermal power plants causes failures as the effects of high temperature, erosion, stress, vibration and corrosion combined to yield failure of the boiler tubes.

In pulverized coal-fired power stations, about 20% of the ash produced in the boilers is deposited on the boiler walls, economizers, air-heaters and super-heater tubes. This deposited ash is subsequently discharged as slag and clinker during the soot-blowing process. The rest of the ash is entrained in the stream of flue gas leaving the boiler. These ash particles collide with the boiler steel components and cause extensive surface erosion and may fail once they lose their structural integrity. Such erosion, together with the processes of blocking, fouling and corrosion, shortens the service-life of boiler components. This leads to forced shut down of power plant in order to replace the damaged components. The resulting penalty is not only the cost of replacing the components but also the cost of stoppage of power production. It is therefore, required to predict the rate of erosion of the coal-fired boiler components in order to plan systematically for the maintenance or replacement of these components and avoid forced outages.

Leading BTF mechanisms include Corrosion Fatigue, Fly Ash Erosion, Under Deposit Mechanisms (Hydrogen Damage and Acid Phosphate Corrosion), Long Term Overheating/Creep, Short Term Overheating, Soot-blower Erosion, Fireside Corrosion (Waterwall, Superheater, and Reheater), etc. Fly Ash Erosion is one of the important cause of BTF. The rate and extent of FAE depends on various parameters viz. particle velocity, angle of impact, particle composition, shape, size & sharpness factor, temperature of particle, surface temperature of tube,

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population density of particles, coal quality, combustion efficiency, erosive resistance of the tube surface including compositional & temperature variations. Particle velocity is the most important parameter as the rate of erosive loss is proportional to the velocity raised to an exponent that ranges between two and four. Particle velocity is driven by the local flow velocity at any particular boiler location. Maximum design bulk velocities are on the order of 15 m/s or less. It has been observed that local velocities in excess of 30 m/s are required to cause fly ash erosion failures in 10,000 to 50,000 hours.

It is clear that to predict the fly ash erosion; it is required to know the velocity and temperature of flue gases in various zones of the boiler. It is not practical to measure the real time velocities of flue gases in all zones of the boiler when it is in operation because of cost, clean environment needed for sensing instrument due to presence of flue gas and fly ash, though the temperatures can be monitored. Computational Fluid Dynamics was the obvious choice as the analysis involves fluid flow. However, owing to complex 3D geometry of the boiler, it was beyond the scope of the project to develop indigenous code for solving fluid flow equations. Hence, it was decided to use one of the commercially available CFD codes like FLUENT, CFX etc. FLUENT was chosen for the purpose.

II. GEOMETRIC MODELLING OF THE BOILER

A 210 MW pulverized coal fired boiler from one of the thermal power stations in Maharashtra was considered for investigation. The boiler components include boiler drum, tangentially fired furnace, water walls, water wall platen (WWP), primary super-heater (PSH), cold re-heater (CRH), hot re-heater (HRH), final super-heater (FSH), low temperature super-heater (LTSH), economizer (ECO) and air pre-heater. Detailed drawings of these components and overall drawing were obtained from the power plant for developing the model. A geometric model of the flue gas path containing the tube bundles of WWP, PSH, CRH-HRH, FSH, LTSH, ECO was developed to the actual scale using Pro-E Wildfire 4.0. Flue gas path from above of the furnace and up to the outlet of economizer is considered. Air pre-heater is not considered for analysis. The efforts were taken to ensure the correctness of the geometry. (Fig. 1 & 2)

A. Meshing

Meshing is the intermediate step between the geometric modeling and the flow analysis. Gambit 2.4.6 is used for meshing of geometry. A dense arrangement with large number of tubes in each bundle made the model complex and hence was difficult to be meshed with the limited computing resources. In order to overcome this situation, it was decided to simplify the model. Literature survey revealed the porous media concept which could be used to solve such tube banks problems. In this approach, the tube bank is replaced with a porous block having equivalent overall dimensions and properties like porosity, inertial resistance, etc. which are calculated from original tube bank model.

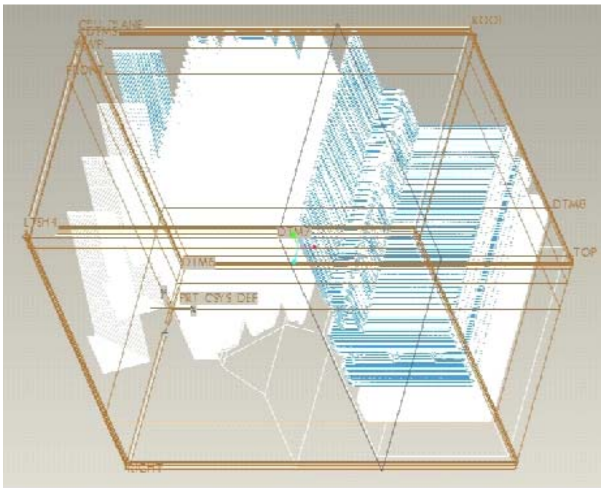

Fig. 1. 3D view of the boiler model. Boiler geometry showing all pressure parts.

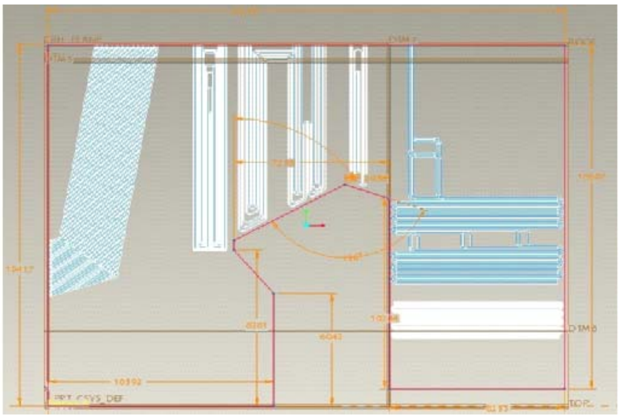

Fig. 2. 2D view of the boiler model. Boiler geometry showing all pressure parts. The fig shows the domain of interest.

The model was developed by replacing the tube bundles with the porous block enveloping the tube bundles. This was done for PSH, CRH-HRH, FSH, LTSH, ECO. LTSH was divided into two parts LTSH Strip which is like wall of single tubes and LTSH Main which contains upper and lower tube banks. WWP has only four platens, which means it is not as dense as other tube bundles. So, meshing was possible without need to convert WWP to porous medium. This model was then meshed with tetrahedral cells. (Fig. 3).

B. Porous Media Approach

The porous media model can be used for a wide variety of problems In this case, a tube bank is replaced with a porous block having equivalent overall dimensions (Fig. 4). When using this model, a cell zone is defined in which the porous media model is applied and the pressure loss in the flow is determined via user inputs.

Heat transfer through the medium can also be represented, subject to the assumption of thermal equilibrium between the medium and the fluid flow. The porous media model incorporates an empirically determined flow resistance in a region of model.

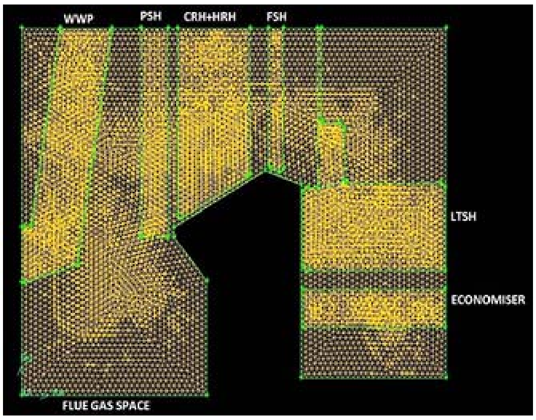

Fig. 3. Meshed porous components and flue gas space.

In essence, the porous media model is nothing more than an added momentum sink in the governing momentum equations. To balance the momentum loss, correct value of inertial resistance is given as input in FLUENT.

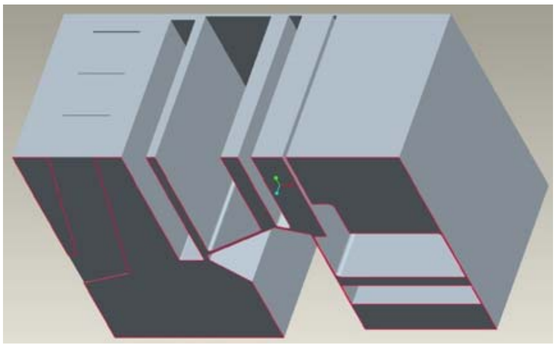

Fig. 4. Boiler Geometry with Porous blocks for pressure parts with equivalent inertia resistance.

We cross checked the pressure drop obtained in module with input value or else checked the mass flow rate over the tube bundles. The mass flow rate should match with the expected mass flow rate of flue gases or air in case of Cold Air Velocity Test. Following table gives the initial calculations of inertial resistances of various zones in case of cold air velocity test simulation. The air at atmospheric temperature is a flowing fluid over the tube bundles. No heat transfer is considered in CAVT simulation between the flowing fluid i.e. air and tube bundles. More information about CAVT is given in subsequent discussion.

TABLE I
INITIAL CALCULATIONS OF INERTIAL RESISTANCE FOR COLD AIR VELOCITY TEST SIMULATION

Zone	PD mmWC	Velocity m/s	Thickness (m)	Density (kg/m^3)	I.R. (1/m)
PSH	1	8	1.5577	1.225	0.161
RH	8	9	2.97182	1.225	0.532
FSH	6	12	0.84773	1.225	0.787
LTSH STRIP	0.5	13	0.2445	1.225	0.194
LTSH MAIN	16.5	13	4.545	1.225	0.344
ECO	17	14	2.0395	1.225	0.681

The porosity of the porous medium is defined as

$$\varphi = \frac{\text{void volume in porous medium sample}}{\text{total volume of porous medium sample}}$$

TABLE II
RESULTS OF POROSITY CALCULATIONS

Zone	Tube Volume (Solid) (mm^3)	Void Volume (mm^3)	Total Volume (mm^3)	Porosity (φ)
PSH	8.005E+10	2.11E+11	2.19E+11	0.96352
RH	3.91E+10	4.58E+11	4.97E+11	0.92137
FSH	1.198E+10	6.849E+10	8.047E+10	0.85112
LTSH Strip	5.92E+09	2.54E+10	3.13E+10	0.8112
LTSH Main	6.591E+10	4.42E+11	5.08E+11	0.87029
ECO	4.032E+10	1.80E+11	2.20E+11	0.81682

III. COLD AIR VELOCITY TEST

It is difficult to physically measure velocities of flue gases inside the boiler when it is in operation. However, it is required to know the velocity flow field in various zones so that its effect on the various failure mechanisms can be predicted. The primary tool to combat Fly Ash Erosion is flow modification in conjunction with a cold air velocity test before and after modification. The cold air velocity test is performed to predict the velocities in the respective zones of the boiler. In this approach, units are evaluated by the cold air velocity technique (CAVT) to determine local velocity profiles, maximum local velocities of two or more times the nominal velocity have typically found, and these peak velocities usually correspond to the locations of known tube erosion damage. The use of CAVT to identify regions of excessive velocity, followed by the installation of diffusion and distribution screens, may provide utilities with the most optimum solution to the problem. However, the technique has not been adopted by sufficient utilities. The results of this CAVT obtained from the concerned power station are used for validating the model developed for predicting the velocity of flue gases.

A. SIMULATION OF CAVT USING FLUENT

The actual geometry of the flue gas path of the boiler created using Pro-E and meshed using GAMBIT is imported in FLUENT for analysis. The inlet and outlet are given pressure boundary conditions. The k-epsilon realizable is used as turbulence model. The results obtained are then compared with the experimental data of CAVT to validate the model. For comparing the results, the points where the actual CAVT is performed are replicated in the simulated model. The planes considered for this are top of LTSH upper bank, bottom of LTSH upper bank, top of LTSH lower bank, bottom of LTSH lower bank and top of Economizer.

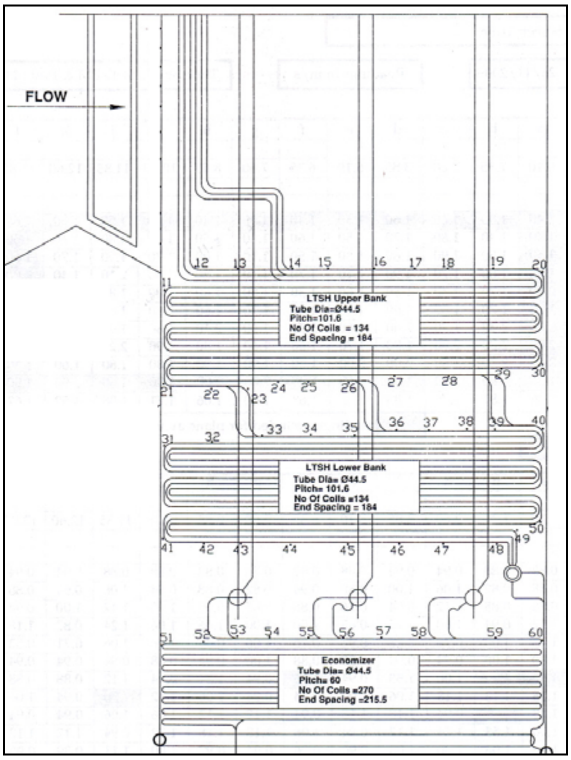

Fig. 5. Positions of Reference Planes

IV. RESULTS AND DISCUSSIONS

From the zone-wise comparison of the values of cold air velocities obtained from onsite CAVT and predicted CAVT, it can be observed that there is considerable difference. Furthermore, on carefully observing the graphs it can be seen that the predicted CAVT gives more or less uniform distribution of the velocity over the plane under observation.

TABLE III
COMPARISON BETWEEN PREDICTED AND EXPERIMENTAL VELOCITIES

Plane	Experimental Velocity (m/s)	Predicted Velocity (m/s)	% RMS ERROR
Top of LTSH Upper Bank	1.89	1.49	21.75
Bottom of LTSH Upper Bank	1.74	1.47	17.17
Top of LTSH Lower Bank	1.62	1.43	13.55
Bottom of LTSH Lower Bank	1.89	1.29	31.98
Top of ECO	1.82	1.34	26.63

On the reference plane "Bottom of LTSH Lower Bank", the error is the highest i.e. around 32%. The reasons for these errors can be attributed to various assumptions and simplification of theoretical analysis owing to lack of computational resources. The exact physical phenomenon has not been modeled while analyzing the flow of cold air through the boiler over the tube bundles. Detailed error analysis needs to be done . Few of the sources of error are (i) Porous Media Approach (ii) Coarse Meshing, (iii) Geometry errors. However, it can be seen from fig. 6 that the trend of predicted CAVT is more or less similar to that of experimental results. There is an offset error between the two.

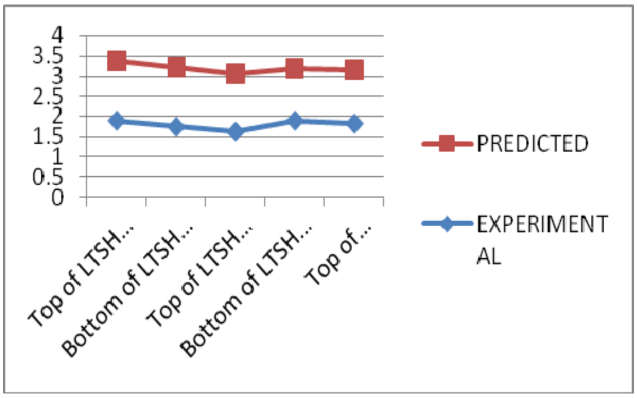

Fig. 6. Trends of predicted and experimental velocities

Thus, from the above error analysis, though we are not able to quantify the amount of error involved in the prediction, we can conclude that the results can be fairly predicted, on an average, within the range of ±25%. This error range may reduce to ±10% on proper mathematical error analysis of above mentioned sources of errors.

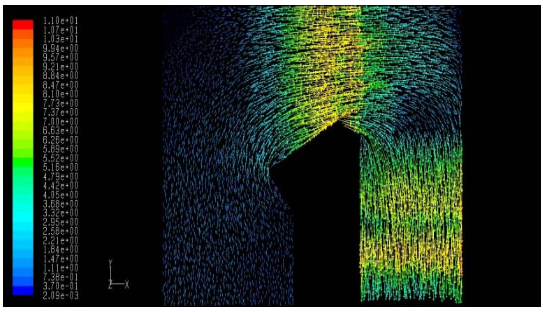

Fig. 7. Velocity vectors, Ref. Plane- 0.1 m from left wall

Figures 7, 8 and 9 show the velocity vectors of the cold air through the boiler flue gas path. Planes 0.1 m and 13.87 m from the left wall of the boiler are near the boiler walls. These planes pass through the gaps between the tube bundles and boiler walls. Hence, there is increase in the velocity of air due to throttling process occurring due to change in the cross section. Increase in the velocity is more prominent in the gaps between the boiler walls and FSH or LTSH or Economizer. These figures also reveal that there is increase in velocity near the walls. In the economizer zone there is increase in velocity near the bends which is responsible for the erosion.

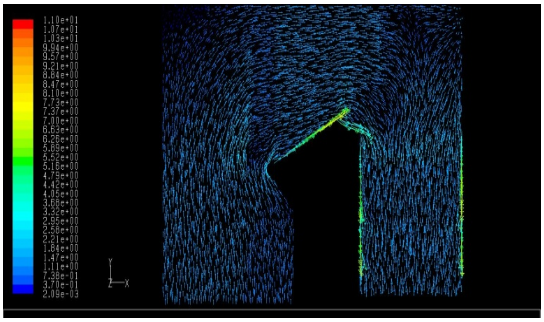

Fig. 8. Velocity vectors, Ref. Plane- 7.60 m from left wall

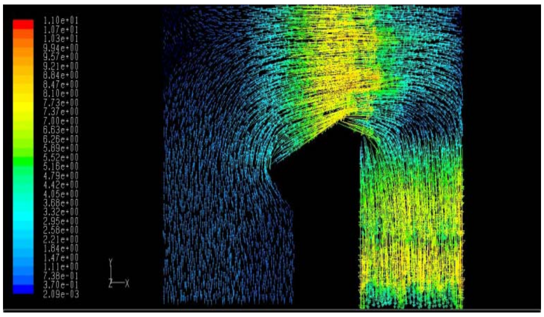

Fig. 9. Velocity vectors, Ref. Plane- 13.87 m from left wall

V. CONCLUSIONS

Cold Air Velocity Test is successfully simulated using FLUENT. The results of the simulation are in good agreement with the experimental results of CAVT with the error of order of ±23 %. The sources of errors and their effect on the model in deviation of the conditions from the actual ones are discussed. This model can be used to predict the velocity of flue gases by changing the boundary conditions and material properties of fluid flowing over the tube bundles. Heat transfer model is required to be enabled for this. If the flue gas velocities are predicted successfully, the zones where the velocity of flue gases increases above the critical velocity will be predicted. This critical velocity can be calculated for each zone from wear rate equation which has been developed. Erosion rate can be calculated based on this equation. From this erosion rate, the life of the tube can be determined and in turn the failure of the tube can be predicted.

To reduce the erosion, the velocity flow-field may need to be redistributed. This is possible with the installation of screens near the affected zone. Also the erosion zones which predominantly include economizer can be enclosed in the box. In case of economizer, bends are more prone to erosion as the velocity near bends increases due to throttling of the flue gases between the walls and the tubes. In case of finned economizers, the surface area of the straight tubes is far greater than that of the bends. Hence, enclosing the bends of economizer will not affect its performance.

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