Analysis Of Flow Induced Vibration In Superheater Tube Bundles In Utility Boilers Using Computational Method

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Abstract

Flow induced vibration in tube bundles subjected to cross flow has been known for a long time. In boilers, tube bundles carrying steam or water are subjected to cross flow of flue gases. This flow causes external forces which may generate vibrations and sound in the boiler during their regular operation. These vibrations can result in tube thinning at support points and consequent leakage or damage to tubes, damage to structural attachments as well as insulation cladding provided around the enclosure. Hence, it is required to predict the occurrence of flow induced vibrations early-on and address the problem. This paper focuses on the flow induced vibration phenomenon of vortex shedding and acoustic resonance in horizontal Low Temperature Superheater (LTSH) tube bundles in utility boilers at full load operation. Computational fluid dynamics tools have been used to perform the flow analysis. The results have been used to predict the occurrence of vortex shedding and acoustic resonance phenomenon and to calculate the amplitude of vibration. Validation has been conducted as per experimental results and confirmed that the methodology adopted holds suitable. The sources of error and their effect on the model in deviation of the conditions from the actual ones have also been discussed.

Keywords: Acoustic resonance, Flow induced vibration, Low temperature super heater, Vortex shedding

1. Introduction

Flow induced vibration for tubes subjected to cross-flow have been a subject of investigation the world over. In boilers, tube bundles carrying steam or water are subjected to cross flow of flue gases. This flow causes external forces which may generate vibrations and sound in the boiler during their regular operation. These vibrations can result in tube thinning at support points and consequent leakage or damage to tubes, damage to structural attachments as well as insulation cladding provided around the enclosure. It could lead to forced shutdown of boiler to replace the damaged components. Hence, it is required to predict the occurrence of flow induced vibrations early-on and address the problem to avoid forced outages. Physical measurement of the vibrations in the tube bundles by measuring probes is difficult in the running boiler due to high temperature. So, there is a need to evaluate vibrations in affected regions theoretically. Computational Fluid Dynamics tools have been found appropriate to perform the flow analysis. Owing to recent improvements in Computational Fluid Dynamics, simulation and flow analysis for tube bundles is now practicable for industrial purposes. Schroder and Gelbe [2] performed two and three dimensional CFD simulation of flow-induced vibration excitation in tube bundles. Dhamangaonkar et. al [5] performed CFD analysis to simulate flow in a typical 250 MW coal fired utility boiler. This paper focuses on the flue gas flow distribution in the in the Low Temperature Super Heater (LTSH) tube bundles situated in second pass of a utility boiler (Figure 01) and the phenomenon of flow induced vibration. Commercially available computational fluid dynamics tools have been used to model the flow domain and perform the flow analysis. GAMBIT has been used for modeling and FLUENT for flow analysis. The phenomenon of vortex shedding and acoustic resonance has been found to occur in the boiler.

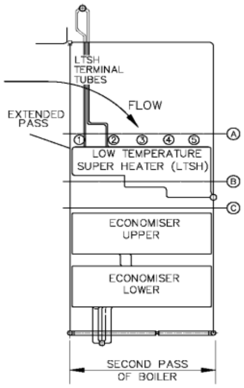


Figure 1: Boiler second pass with reference location for velocity and displacement measurement

2. Vortex Shedding And Acoustic Resonance

When fluid flows perpendicular to tube bundle staggered or inline, the most common phenomenon is the formation and shedding of vortices in the wake beyond the tubes. [2] The vortex shedding phenomenon can be characterized by a non dimensional parameter known as Strouhal number 'S_u', which gives relation between Vortex Shedding Frequency 'f_v', diameter of tube 'D' and velocity of the flow 'v' as,

$$S_u = f_v . D/v \qquad [1]$$

The value of Strouhal number is based on tube spacing in bundles and diameter of tubes. In this paper, the value of Strouhal number $S_u = 0.31$ and 0.27 based on charts by Chen and Fitzhugh respectively have been considered. [3][4]

The vortex shedding causes a harmonically varying force on the tube perpendicular to the normal flow of the fluid. It is a self excited vibration. If the Vortex Shedding Frequency 'f_v' coincides with the Natural Frequency of vibration of the tubes 'f_n', resonance occurs and tubes vibrate, leading to tube leakages and structural damages. The condition is :

$$0.8f_n < f_v < 1.2f_n \qquad [7]$$

Another mechanism associated with vortex shedding is the acoustic resonance. Acoustic resonance may take place when vortex shedding frequency coincides with Acoustic Frequency 'f_a' of standing waves in the enclosure. The condition is given as,

$$0.8f_a < f_v < 1.35f_a \qquad [8]$$

The acoustic frequency due to gas flow in the passage considering width of boiler 'L_a', effective speed of sound in bundles' C_{eff}' , and acoustic modes 'n' is given by the relation,

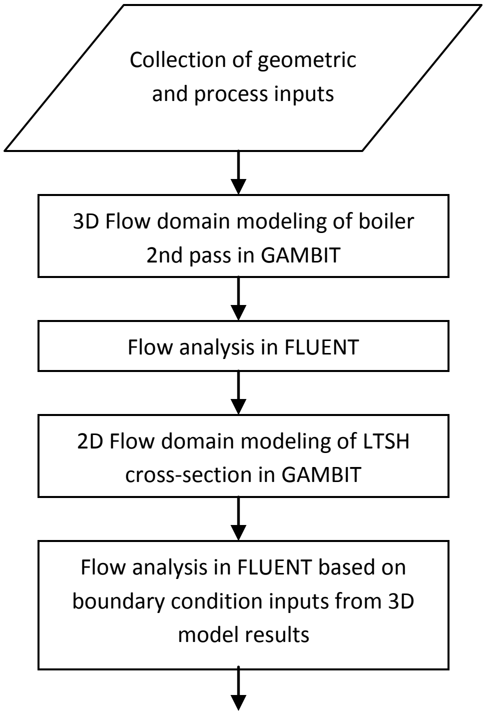
$$f_a = n.\ C_{eff}/2.L_a \qquad [12]$$

The effective speed of sound through the tube bundles, is related to speed of sound in the empty passage 'C' and the solidity ratio of the tube bundle 'σ' by the relation,

$$C_{eff} = C/(1+\sigma) \qquad [12]$$

3. Methodology

In this paper, flow induced vibration mechanisms described above have been studied for LTSH tube bundles. For this, the 3D flow domain of boiler enclosure with LTSH has been modeled in GAMBIT and analyzed in FLUENT to study the flow distribution. A 2D model of cross-section of LTSH tube bundle has also been made to study the flow distribution inside the tube bundle. Velocity of flue gases obtained from the flow analysis has been used to calculate f_v. A comparison of fv with f_n and f_a has been made to predict the vortex shedding phenomenon. Validation was conducted as per site measured values and confirmed that the methodology adopted holds suitable.



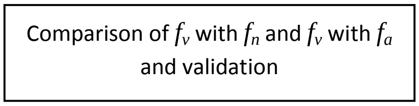


Figure 2: Flow chart for approach followed

3.1 3D Model for second-pass of boiler

A 3D model of boiler second-pass pass up to LTSH has been developed in GAMBIT for a typical 210MW utility boiler. The LTSH tube bundle is a dense arrangement of tubes which makes it difficult to be meshed with the limiting computing resources. For ease of computation, porous media approach has been used. The LTSH terminal tubes and LTSH tube bundle have been modeled as volumes of equivalent dimensions and declared as porous block. The Inertial Resistance (I.R) and porosity for the porous block has been calculated from the original LTSH model. Pressure Drop (PD) across tubes and velocity for calculation has been considered as per the design criterion. Tetrahedral elements have been used to mesh the model as shown in Figure 03. Flue gas has been taken as the fluid medium. The 3D model has been analyzed with velocity inlet and pressure outlet boundary conditions and k-ε has been used as the turbulence model.

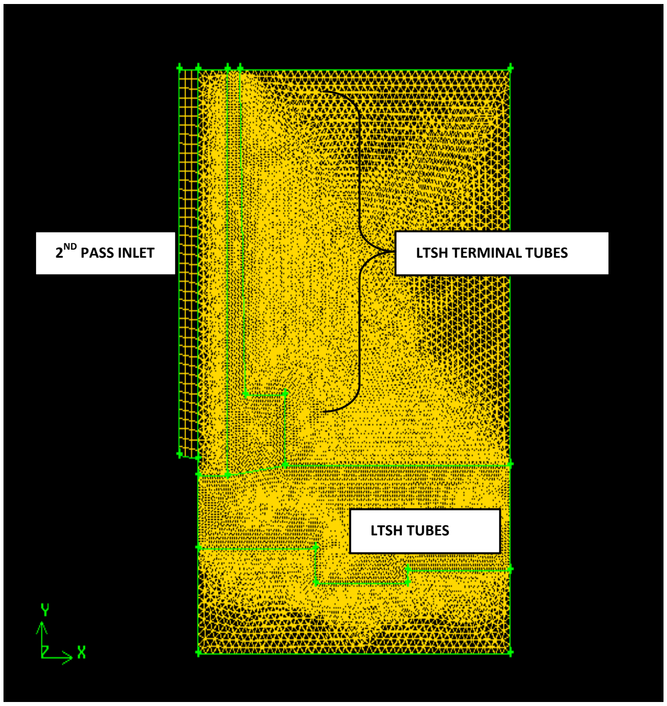


Figure 03: Meshed flow domain with porous components

3.2 2D Model for cross-section of LTSH

The cross-section of LTSH tube bank has been modeled in 2D as shown in Figure 04. First and last three rows of tubes have been modeled and porous media approach has been used for the space in between. The face at inlet, outlet and porous zone has been meshed with quadrilateral elements and the faces with tube cross-section have been meshed with triangular elements as shown in Figure 05. The velocity profiles obtained from the 3D model at five locations above LTSH as shown in Figure 01 have been used as inlet boundary condition and pressure as outlet boundary condition. Flue gas has been taken as the fluid medium and k-ε had been used as the turbulence model.

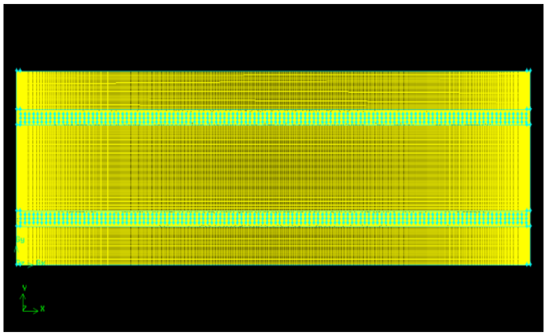


Figure 04: Meshed 2D model of LTSH cross section

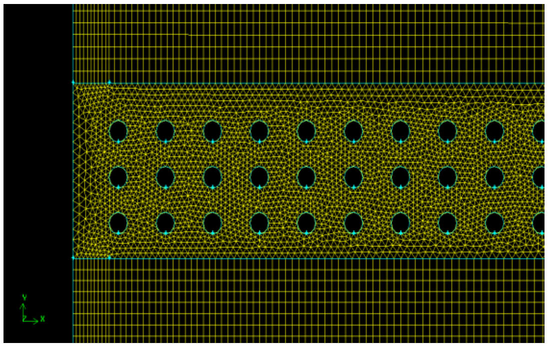


Figure 05: Meshed quad and tri elements

4. Results And Discussions

The flue gas flow changes direction as it flows from extended pass to LTSH tube bundles. The extended pass is tapered. Due to this, the flow enters with a sharp turn in the second pass of boiler. As it is evident from the velocity contour shown in Figure 06, a certain degree of separation occurs in the lower side and the flow distribution cannot be uniform over the transverse direction of the section. As a result, no uniform velocity distribution can occur at the top of LTSH. It can be said that, these tube bundles will be subjected to varying flow along the depth of boiler second pass. Figure 07 shows the variation of average velocity at the inlet of LTSH along the depth at aforementioned locations.

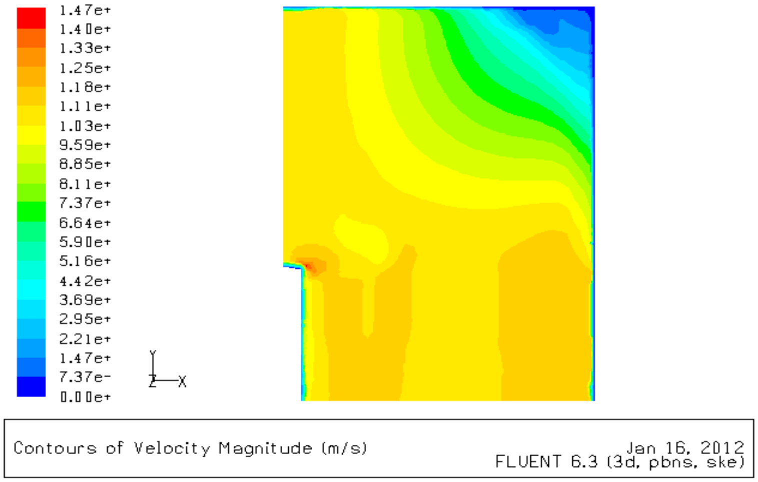


Figure 06: Velocity contour at mid-plane of second pass of boiler

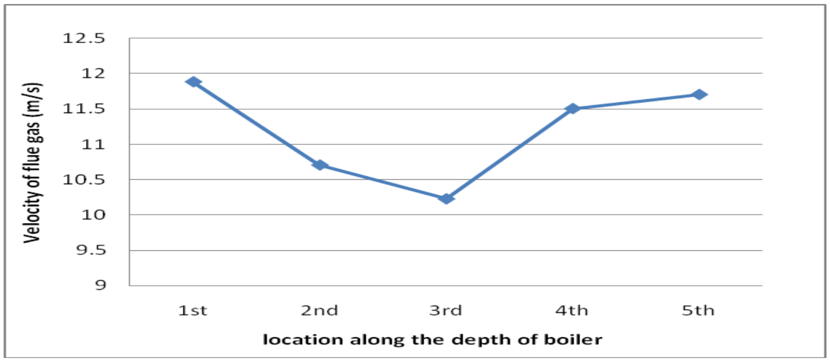


Figure 07: Variation of flue gas velocity at different locations above LTSH along the depth of boiler

To address this non-uniform flow distribution, the velocity profile has been captured at the above five locations along the depth of boiler from the analysis. These velocity profiles serve as inlet boundary condition to the 2D model of cross-section of LTSH. The typical flow pattern obtained for the 2D model of LTSH cross section in Figure 08, shows confined tube wakes as pointed out by Ziada [6]. The flow dynamics in the flow lanes would be expected to dominate the development of the velocity fluctuations within the tube bundle.

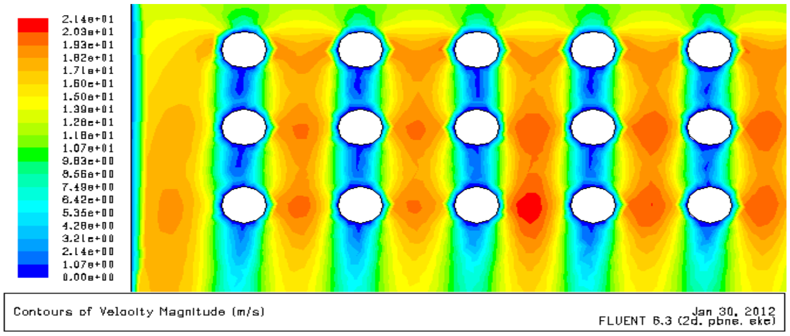


Figure 08: Typical velocity contour through LTSH cross-section

The average velocities at LTSH outlet obtained from the 2D model analysis has been used to predict the vortex shedding frequency. Table 03 shows the calculated vortex shedding frequency. Table 04 gives the value of natural frequency and acoustic frequency for the first five modes. Comparing vortex shedding frequency according to Chen's criterion with tube natural frequency and acoustic frequency it has been found that tube vibration is possible in 2nd mode. It could increase further at higher load and decrease if the boiler is operated at lower loads. Acoustic resonance is possible at higher nodes. According to Fitzhugh criterion tube vibrations may occur in 2nd mode and acoustic resonance is possible at higher nodes.

Table 03: Average velocity at five locations along depth of boiler and vortex shedding frequency

Location from second pass wall (Fig.01)	Vortex shedding frequency, f_v Chen's criterion (Hz)	Vortex shedding frequency, f_v Fitzhugh criterion (Hz)
1st	82.83	72.14
2nd	74.60	64.98
3rd	71.26	62.07
4th	80.18	69.83
5th	81.56	71.05

Table 04: Natural and acoustic frequency for first five nodes

Modes	Natural frequency, f_n (Hz)	Acoustic frequency, f_a (Hz)
1st	36.50	18.93
2nd	100.62	37.8
3rd	197.27	56.7
4th	326.11	75.72
5th	487.15	94.65

Physical measurement of the vibrations in the tube bundles by measuring probes is difficult in the running boiler due to high temperature. So, actual measurement of amplitude of vibrations was performed at the structures outside the boiler enclosure. The amplitude of vibrations in the tubes has been calculated, based on the flow velocity, at reference elevations A, B & C as shown in Figure 01. [12] A comparison has been shown between the tube vibration calculated and vibration data measured at the left and right hand side of boiler structure side in Figure 09. The difference in the calculated and measured values could be attributed to reasons like; (i) Actual measurement performed at outer structure of boiler and not on tube surface (ii) Porous media approach (iii) Geometry errors. However, on careful observation, it can be seen that the trend of predicted vibrations are more or less similar to the trend of site measured values.

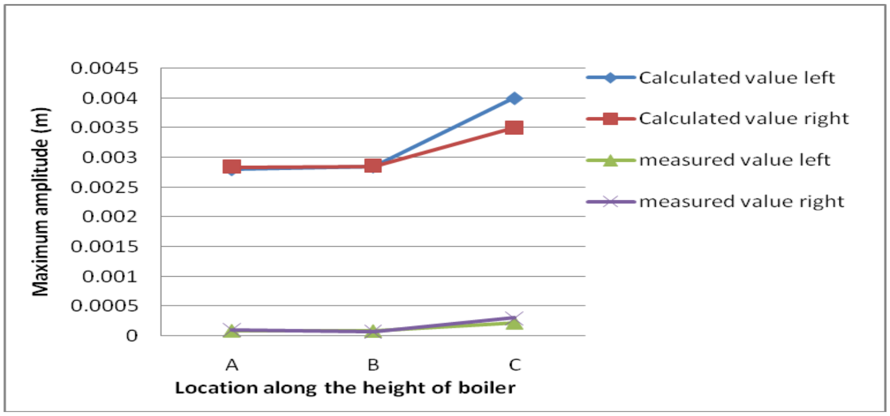


Figure 09: Predicted and measured amplitude of vibration**.**

Tube vibrations can be reduced to within limits by either reducing the cross-flow velocity or increasing the tube natural frequency or suppressing the standing waves. Reducing the cross-flow velocity of flue gas is directly linked to desired steam output parameters and needs careful considerations. By providing additional supports and baffles in between tubes or by removing tubes, the tube natural frequency can be changed and acoustic standing waves can be suppressed.

5. Conclusion

In this paper flow induced vibration phenomenon has been studied for horizontal Low Temperature Superheater (LTSH) tube bundles in utility boilers at full load operation. Flow analysis has been performed using commercial software FLUENT and the results have been used to predict the occurrence of vortex shedding and acoustic resonance phenomenon for LTSH. From the analysis, it has been observed that LTSH receives varying flow distribution along the depth of boiler. The phenomenon for vortex shedding and acoustic resonance has been observed in the boiler. The trend of calculated vibration amplitude at reference elevations has been found to be similar to the site measured values. The sources of error and their effect on the model in deviation of conditions from the actual ones have been discussed. The model can be used to predict vortex shedding and acoustic resonance phenomenon at different operating loads by changing the boundary conditions. Thus an optimum operating load range could be predicted for the boiler to operate avoiding vortex shedding and acoustic resonance phenomenon.

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