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Numerical studies on furnace water walls failure in water tube boiler applications

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Abstract. Boiler as one of the main equipment in steam power plant system that has important function as steam generation for rotating turbine. Failure of boiler result in operational cause lowering the power capacity of the steam power plant system on the whole. From the data observation, boiler failure frequencies because of leakage on boiler tubes. To analyze the boiler tube failure accurately, information of temperature operated on the outer surface tube and temperature distribution on the furnace wall are needed. The main objective of this study is to investigate several areas in which the failure of furnace water walls boiler exists. A combined analysis of thermal and strength of material has been performed, in order to calculate the temperature and velocity fields inside furnace of the water tube boiler. Due to the geometrical complexity of the model, GAMBIT applications was used to generate a computer-based model. All numerical calculations have been performed using the commercial CFD package *FLUENT*. The results obtained were numerically that failure on furnace water walls in water tube boiler because there is localized overheating.

1. Introduction

A boiler is a closed vessel producing heat by the combustion of fuel which is transferred to water for its conversion into steam at desired temperature and pressure. They are vastly used in power plants, paper industry, chemical industries, textile industry, metal work industries and many more [1]. The efficiency of these industries is very much dependent upon boiler's efficiency. Hence, it is necessary to carry out the maintenance of boiler at regular intervals so as to avoid any unwanted shutdown. However, operation of boiler leads to number of problems such as hot corrosion, fatigue failure and failure in water tube boiler which are responsible for their unwanted shutdown [2]. Moreover, fireside of boilers suffers maximum damage. Hence, it is necessary to find the solutions either to avoid or to remove such type of problems in the boiler.

This study is focused on boiler tube failure analysis looking at it from thermal and material aspects. To analyze the boiler tube failure accurately, information of temperature operated on the outer surface tube for keeping saturated steam in the evaporator and information of temperature distribution on the furnace wall are needed. Base on the static load failure theory, by decreasing yield strength and increasing principal stresses then the tube can not restrain stresses that caused by inner fluid stresses thus the tube will yield. Because of the stresses are not higher than the material ultimate strength, so that the tube should not cracked. Because of the fact that the tube has cracked thas it shows that there is localized overheating.

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2. Types of boiler

Boilers can be basically classified into water tube boilers, fire tube boilers, packaged boilers, fluidized bed combustion boiler (FBC), pulverized fuel boiler and waste heat boilers. In this paper is focused on water tube boiler.

In water tube boilers, the water to be heated flows in the tubes and the combustion gases flows around the tubes, thus converting the water into steam. These types of boilers are used where high steam and pressure are required. The capacity of these boilers varies from 4,500 to 120,000 kg/h [3]. Water tube boilers are the least used boilers now-a-days. In this boiler, combustion products and high temperature gases flow in the tubes and water to be vaporized flows around these tubes. The capacity of these boilers is up to 12,000 kg/h. They produce low to medium steam pressures up to 18 kg/cm^2 [4]. The one example is the Steam power plant (PLTU#1) at PT. PJB UP Gresik, in East Java, Indonesia. The maximum output of energy is 100 MW, and the steam values produced by the unit are 98 bar and 310^{o}C [5].

3. Problems being faced in the boilers

Major problems occurring in the water tube boilers used fuel oil are high temperature corrosion, fatigue failure and wear in water walls. This paper is focused in fatique failure and wear in water walls.

3.1. Fatigue failure.

The propensity of a material to fracture by means of continuous brittle cracking under repeated alternating or cyclic stresses of intensity fairly below the normal strength is known as fatigue failures [6]. They are caused by high value of maximum tensile strength, high amount of variation in applied stress, attachment of corrosion welds, improper flexibility, improper heat treatment, contouring of welds, large number of cycles of applied stress and cold-bend restriction to thermal expansion [6]. Managing water walls tube boiler failures is important as it can help in reducing forced outages, minimize risk of failures and hence, improve plant availability as well as reliability.

One of the most important causes boiler tube failure, that is fatigue failures. They can be prevented by following: avoid stress concentrations, pay careful attention to the details at design stage to make sure that cyclic stresses are sufficiently low to attain the required endurance, use stronger and more capable materials with high fracture toughness and slow crack growth, choose good surface finishes, monitor temperature variations, increase symmetry, resolve simplicity of design and ensure firm as well as thorough routine maintenance [7].

3.2. Failure in water tube boiler

All mechanical components containing moving parts are susceptible to wear. At low temperatures, mechanical wear rates can be controlled with lubricants and material selection. In water tube boiler, most moving parts are located outside the boiler itself, and do normally not require any special attention. The type of wear that must be taken into special examination is abrasion caused by moving particles. Combined with high material temperatures, the wear rates may be excessively high. The boiler components which are mostly exposed to abrasive wear are parts which are in direct contact with the solid material. The suspension density of the solid material is at largest in the low region of the furnace, gradually decreasing towards the furnace roof. The risk of material wear is greatly reduced as suspension density decreases. Another area with high suspension density is inside the solids separator, especially in the gas inlet and outlet channels. Together with the solids suspension density, another key issue is material temperature: at elevated temperatures, most materials have lower resistance againt corrosion. If a piece of equipment is located at place where both the particle density and velocity, and the material temperature are high, the risk of material wear is evident. Different boiler component shows different wear behavior depending on the location and operating temperature [8].

4. Methodology

The present study uses computational fluid dynamics (CFD) to investigate furnace water walls wear in PLTU#1 PT. PJB UP Gresik. Since experiments are very difficult to perform during intensive care stays in the field when Water tube boiler is at operation, numerical simulations may be very useful in many situations. Such procedure can provide an operational data and assist in the design of more efficient [9].

4.1. Model geometry

In the previous studies, a simplified model of fuel oil combustion and wall fired furnace were adopted, usually represented by geometric of the furnace water walls for boiler [8,9]. Dimensions required to build the representation of the furnace water walls for Water tube boiler was obtained from technical documentation provided by manufacturer. Some additional calculation and measurement were also taken as boundary and initial conditions. The complete model can be seen in Fig. 1. The stage of pre-processing that are modelling furnace geometry, discretized of furnace geometry into mesh element and applying boundary conditions at geometry walls. This stage is used by pre-processor GAMBIT. Furnace geometry is divided into six parts based on zone of temperature gradient as can be seen at Fig. 1. The Zone 1 is area around burner, zone 2 is furnace upper area, zone 3 is area under burner, zone 4 is secondary superheater, zone 5 is primary superheater, and zone 6 is secondary-primary superheater zone.

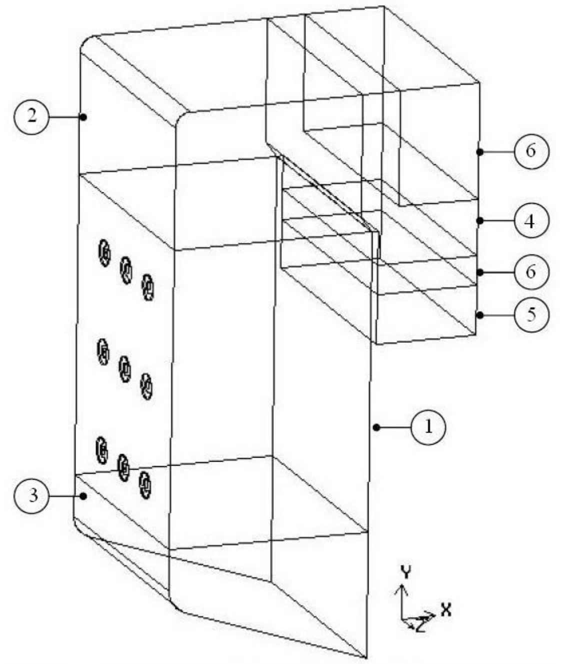

Figure 1. Geometry model of furnace [10].

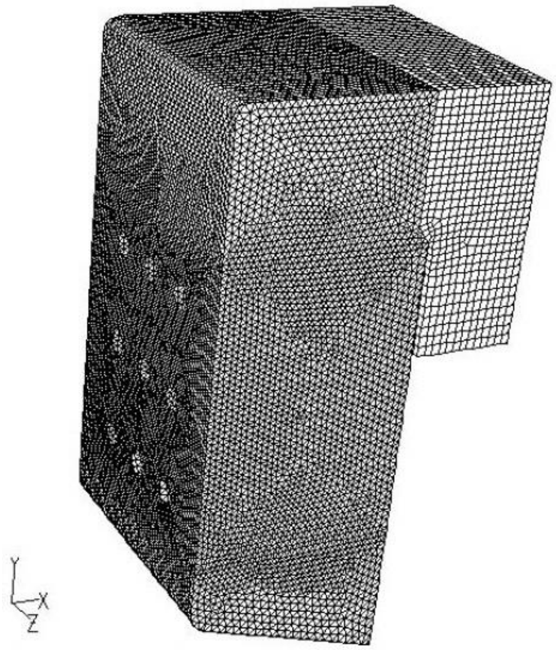

Figure 2. Furnace water walls meshed [10].

4.2. Model discretization

The entire mesh generation process was performed by the pre-processor GAMBIT [10]. The mesh used in the model is unstructured and grid contains about 459,966 tetrahedral, hybrid and hexagonal elements and 99,618 grid (see in fig. 2).

Basic assumptions and calculation in the mathematical model that used in this paper are:

- Steady-state model of the combined heat and mass transfer processes;
- All test are performed in Fluent in 3ddp (3D double precision) [10];
- Combustion and turbulent model used were species transport and k-epsilon model;
- Heat transfer analysis is based on the energy equation [11].

4.3. Boundary conditions

In this model, the working fluid is represented as a mixture of fuel oil and air and those working fluid have been modelled as hydrocarbon species. Velocity inlet boundary conditions were used to define the velocity and scalar properties of the flow and the six inlet boundaries.

All test is performed in Fluent in 3ddp (3D double precision). This code is based on ordinary conservation equations for mass, momentum and energy. Within the code the used models are energy, realizable viscous model with enhanced wall treatment and species transport. The realizable k-epsilon model is used since it produces more accurate result for boundary layer flows than the standard k-ε model. The gravity is 9.81 m/s^2. The walls are simulated as thinnest solid walls, therefore the wall temperature is assumed close on the inside fluids temperature, i.e. temperature of saturated steam. In Table 1 more details about used material properties for working fluid, air and walls are given.

In all test it was chosen to use an unstructured mesh in order to avoid a guidance of the flow. Furthermore, an unstructured mesh is better at dealing with corners and complex geometry than a structured mesh. Another advantage of the unstructured mesh is that it is much easier to refine in certain zones where more information on the flow or distribution of temperature is valuable. However, the unstructured mesh can cause problems near the walls and this is compensated for by use of a so-called enhanced wall treatment [12].

5. Result and discussion

All simulations have been continued for 1600 iterations. After the iterations the residuals found for continuity are in the range $6.88 \cdot 10^{-6}$ until $2.38 \cdot 10^{-3}$, which is low and hence convergence is assumed reached. The result of numerical study is shown in form temperature contour, gas velocity and gas velocity vector at the region predicted overheating exist. The temperature contour at Z- and Y axis is shown in fig. 3.

Figure 4 shows calculation result for the gas temperature contour at the plane intersect burner A2, B2 and C2 (plane projection at Z = 433 cm). At the fig. 4 shows that gas temperature at the bottom furnace (the region under burner A) has average temperature higher compared with other region, i.e. 1,000 to 1,070°C. Figure 5 to 6 shows calculation result for gas velocity contour and gas velocity vector in plane projection at Z = 433 cm, respectively. Both of the figure explain the high temperature at the bottom of the furnace. At the fig. 7 can be seen stagnant region where gas velocity was small.

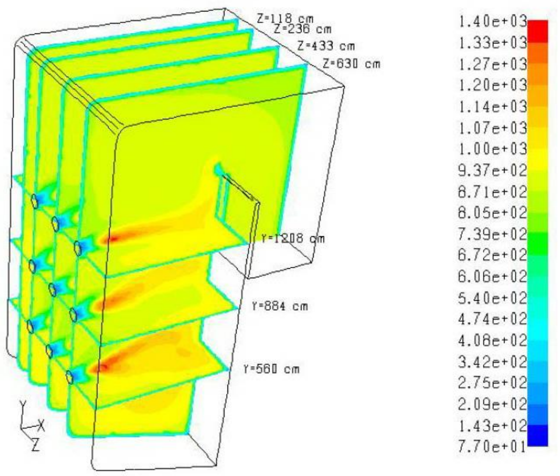

Figure 3. Contour of static temperature at Z- and Y axis.

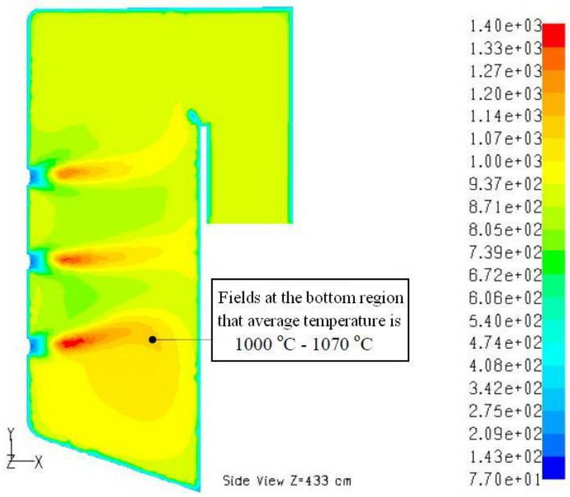

Figure 4. Temperature contour at plane projection Z = 433 cm.

The presence gas trapped at vortex region cause temperature is very high at this region. This condition may generate which initiate furnace water walls wear. To proof the evident of localized overheating, need the information of temperature distribution around furnace. Therefore, Fluent calculates temperature contour of projection plane at Z = 118 cm as shown at Fig. 7. At this figure, has been appeared the region has temperature contour between 1,164 to 1,236°C, that means higher than area around the furnace.

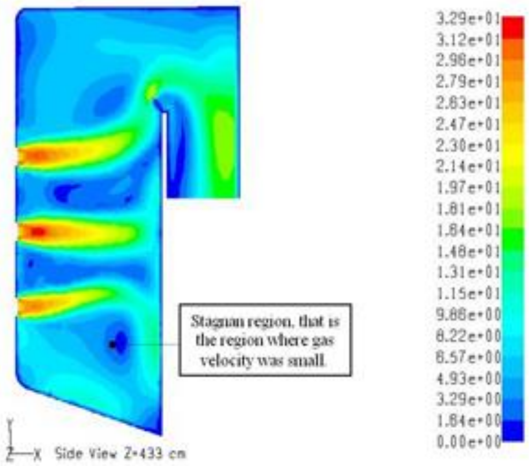

Figure 5. Velocity contour at plane projection Z = 433 cm.

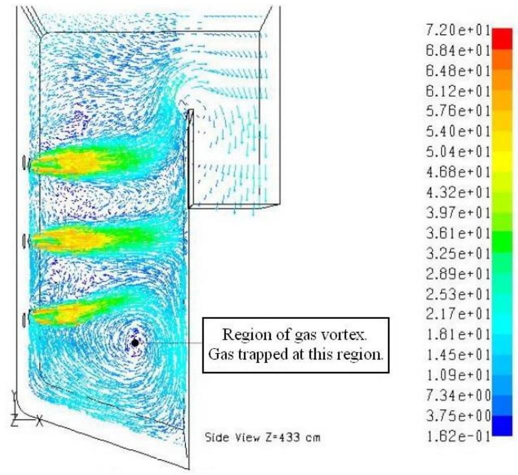

Figure 6. Velocity vector at plane projection Z = 433 cm.

The presence of hot spot field as shown at Fig. 7 prooved that in this region happened localized over-heating. With the range gas temperature between 1,164 to 1,236°C, flame temperature 1,525°C, therefore temperature of outside pipe surface, T_{0s} is 803 to 947°C. It means, average temperature T_{0s} is 900°C cause strength of pipe material went down become yield strength (σ_y) and ultimate strength (σ_u) are σ_y = 12,507 psi and σ_u = 18,646 psi, respectively, as shown at Fig. 8.

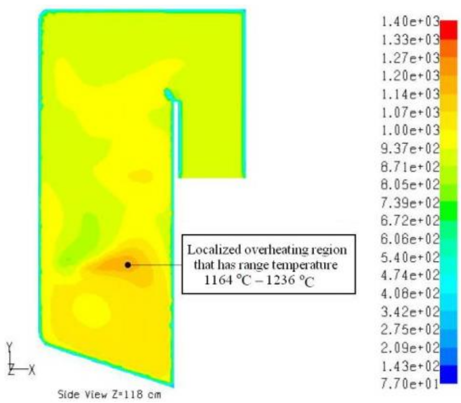

Figure 7. Temperature contour at projection Z = 118 cm.

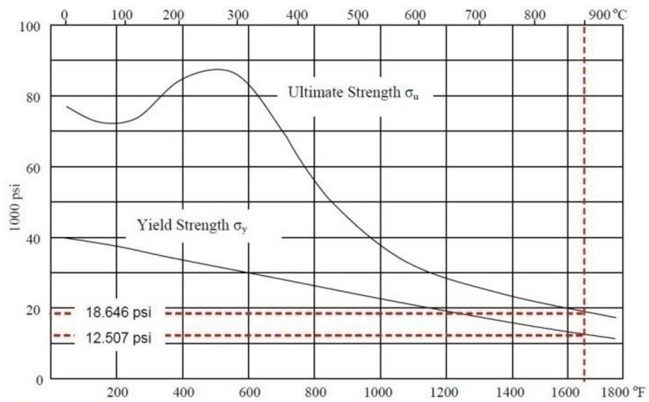

Figure 8. Strength of pipe material at 900 °C [13].

The following is strength of pipe material studies regarding furnace water walls failure [13].

- Principal stress 1 (σ_1), i.e. maximum normal stress:

$$\sigma_{1(r=r_i)} = K_1 \left[1 + \left(\frac{r_0}{r_i} \right)^2 \right] \tag{1}$$

- Principal stress 2 (σ_2), i.e. minimum normal stress:

$$\sigma_{2(r=r_i)} = -p_i \tag{2}$$

where

$$K_1 = \frac{p_i r_i^2}{r_o^2 - r_i^2};\ p_i = 100{,}5 \text{ bar} = 1.005 \cdot 10^7 \ \text{N/m}^2;$$

$r_i = 0.02775$ m and $r_o = 0.02955$ m

If eq. 1 and 2 is executed:

$$\sigma_1 = 1.005 \cdot 10^7 \left(\frac{0.02955^2 + 0.02775^2}{0.02955^2 - 0.02775^2}\right) \cdot \frac{1}{6{,}894.8} = 23{,}223 \text{ psi}$$
$$\sigma_2 = -1.005 \cdot 10^7 \cdot \frac{1}{6{,}894.8} = -1{,}458 \text{ psi}$$

With principal stress σ_1 = 23,223 psi, σ_2 = −1,458 psi, τ_{max} = 12,340 psi and σ_{eq} = 22,537 psi, therefore based on third static load failure theory furnace water walls will be broken.

6. Conclusion

The result of numerical studies have showed that at the bottom area of Water tube boiler combustion happen gas stagnation and gas flow field vortex. The presence of gas stagnation region cause the increased higher temperature than other region. Fluent calculated at the region gas vortex the temperature is between 1,164 ^{o}C to 1,236 ^{o}C. It has been shown that at the range temperature this, the strength of pipe material will be decreased and already prooved that furnace water walls will be broken.

In water tube boiler combustion, the presence of hot spot field creates an increase of furnace water walls wear. When high temperature of combustion is combined with erosion-corrosion, resulting may rapid metal degradation [14]. The most critical parts may be made of special materials, such as metal matrix composites made by powder metallurgy. With metal matrix composites, ordinary welding is seldom possible. The increased material cost is eventually paid back by increased availability and much longer material lifetime.

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