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Numerical Analysis of the Performance Characteristics of Elliptical Circulating Fluidized Bed (CFB)

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Abstract: **This research work numerically analyze the elliptical CFB boiler tube model using Ansys 15.0. The detailed analysis has been done for performance parameters such as temperature distribution, heat transfer coefficient on elliptical CFB boiler tube models. The result has been compared with the reference paper reported in the literature. This paper also shows the comparison of elliptical CFB boiler tube with fin configured CFB model at constant temperature.**

Index Terms **- Computational Fluid Dynamics, Simulation, Conductivity, Heat Flux, Boiler**

I. INTRODUCTION

The circulating fluidized bed (CFB) is a developing technology for coal combustion to achieve lower emission of pollutants. By using this technology, up to 95% of pollutants can be absorbed before being emitted to the atmosphere [1].Fluidization is the phenomenon by which solid particles are transported into a fluid like state through suspension in a gas or liquid. In fact, there is a simple and precise way to classify the various fluid-particle beds. Most of the CFB operating and environmental characteristics are the direct results of the hydrodynamic behaviour [2]. Numerous of searchers have studied the hydrodynamics of CFB. The fluidization is a function of several parameters such like the particles' shape, size and density, velocity of the gas, bed's geometries etc. Many researchers defined the regimes of fluidization as described below:

[1] **Fixed Bed:** When the fluid is passed through the bottom of the bed at a low flow rate, the fluid merely percolates through the void spaces between stationary particles.

[2] **Minimum fluidization:** When the gas velocity reaches (U_{mf}) minimum fluidization velocity, and all the particle are just suspended by the upward flowing fluid.

[3] **Bubbling Fluid Bed:** When the flow rate increases beyond the minimum fluidization velocity, bed starts bubbling. The gas-solid system shows large instabilities with bubbling and gas channeling with rise in flow rate beyond minimum fluidization. Such a bed is called aggregative, heterogeneous, or bubbling fluidized.

[4] **Turbulent Fluidized Bed:** When the gas flow rate sufficiently increases, the terminal velocity (U_{tr}) of solids is exceeded, the upper surface of the bed disappears, entrainment becomes appreciable instead of bubbling,

[5] **Fast Fluidized Bed:** With further increasing in gas velocity, solids are carried out of the bed with the gas making a lean phase fluidized, this regime is used for operating CFB. In the present work, fast fluidized bed is used to operate the CFB where the pressure drop decreases dramatically in this regime.

[6] **Pneumatic Transport:** Beyond the circulating fluidized bed operating regime, there is the pneumatic transport region, pressure drop increases in this regime.

An appreciated contribution by Geldart's classified the particles based on size and density into four groups viz. C, A, B, and D. Group B (of particle size d_p between 40-500 μm and density of ρ_s<~1400 kg/m^3) is commonly used for CFB. Yang modified Geldart's classification using Archimedes number Ar, under elevated pressure, temperature, and non-dimensional density.

Pressure and Pressure Drop The flow in a CFB is multiphase. The unrecoverable pressure drop along the riser height is a basic value for design, and these results due to solid particles distribution, voidage, gas viscosity, gas velocity, gas density, and density of solid [3, 4].

1.1. Basic of Technology

During the combustion phase, upwards jets of air will cause the solid fuels to be suspended. This is to ensure the gas and solids will mix together turbulently for better heat transfer and chemical reactions. The fuel will be burnt at a temperature of 1400°F (760°C) to 1700°F (926.7°C) to prevent nitrogen oxide from forming. While burning, flue gas such as sulfur dioxide will be released. At the same time, sulfur-absorbing chemical such as limestone or dolomite will be used to mix with the fuel particles in the fluidization phase, which will absorb almost 95% of the sulfur pollutants [5].

Alternatively, the sulfur absorbing chemical and fuel will be recycled to increase the efficiency of producing a higher quality steam as well as lower the emission of pollutants. Therefore, it will be possible to use circulating fluidized bed technology to burn fuel in a much more environmental friendly method as compared to other conventional processes.

1.3 Principle Process Characteristics

The circulating fluidized bed reactors have been widely used in various industrial processes such as gasification and coal combustion. Though the circulating fluidized beds are used widely, the CFD, which can be, describe by non-uniformity flow patterns and a thorough back mixing still possess significant radial gradients in the particle density and a lower solid holdup inside the riser interior compared to the wall of the reactor. These events will then result in low contact efficiency. For the case of catalytic gas-phase reaction process, gas back mixing should be avoided thus the reacted product is the gas phase. Another characteristic of the circulating fluidized bed is, as it required promoting the small contact time of gas and solid catalyst and plug flow, a significant high gas velocity in the riser is needed. The significant high gas velocity in the riser is also desired to fulfill the necessity in the catalytic gas-phase reaction.

1.3.1 Design and Operation

The circulating fluidized bed involves basically two balancing characteristics of the gas-solid system through Hunter Kowald, which are the design and the operation characteristics.

Recirculating loop of particles occurred when entrained particles, which possess a substantial amount of flux, are separated efficiently and externally to the reactor from a giant core reactor (riser) from its carrying fluid and will then be circulated back to the bottommost of the riser. The carrying fluid will circulate around this loop only once however the particle will pass through several times before finally leaving the system. The schematic diagram of a typical circulating fluidized bed can be seen in Figure 1.1 below.

The system is usually operated under high particle flux and high superficial gas velocity, which are typically (10–1000 kg/m^{2}s), and (2–12 m/s) respectively. This operational condition is chosen to avoid a distinct interface between the dilute region and the dense bed inside the riser. Thus gas velocities above the bubbling point is chosen for contacting. The standard operating conditions for the circulating fluidized bed can be seen in Table 1.1 below.

Table 1.1: Typical operational condition for circulating fluidized bed [6]

S. No.	PARAMETERS	ACCEPTED VALUES RANGE
1	Superficial gas velocity (m/s)	2–12
2	Net solids flux through the riser (kg/m2s)	10–1000
3	Temperature (°C)	20–950
4	Pressure (kPa)	100–2000
5	Mean particle diameter (µm)	50–500
6	Overall riser height (m	15–40

The circulating fluidized bed (CFB) use high fluid velocity to provide better gas-solid contact by providing more intense mixing of the fluid so that better quality of product can be obtained. However, the high gas velocities and the recirculation of solids may make the CFB system much more expensive in term of power requirement and investment compared to conventional fluidized bed reactors [7]. CFBs have been widely used in the field of solid catalyzed gas phase reactions in two situations below.

[1] Continuous regeneration of catalyst, which deactivates rapidly. The solid is maintained in constant circulation where catalyst is continuously regenerated and return to the reactor.

[2] Heat must be brought in or removed from a reactor. A continuous circulation of solids between vessels can efficiently transport heat from one vessel to another since solids have relatively large heat capacity compared to gases.

One important factor of circulating system is the ability to control the feed circulation rate. The feed circulation rate is control by the gas velocity in the bed which determines the flow regime and density of bed. All the circulating systems can be characterized either by the solid circulation rate, kg/s and the transfer ratio of the suspended materials being exchanged between vessels. For circulating fluidized bed in coal combustion, the beds need to use a greater fluidizing speed, so the particles will remained constant in the flue gases, before moving across the combustion chamber and into the cyclone. During combustion, a dense bed is required to mix the fuel even though the solids are dispersed evenly all over the unit. The bigger particles are extracted and returned to combustion chamber for further process, which required relatively longer particle residence time. If the total carbon conversion efficiencies gets over 98% it shows good separation process that leaves simply a minor proportion of unburned char in the residues. During the whole process, the operating conditions are relatively uniform for the combustor [8].

The objective of the proposed research work is to validate the ANSYS analysis of simulations result of elliptical CFB boiler tube models by comparing the results of base paper reported in the literature. To perform analysis of the performance parameters of temperature distribution, heat transfer coefficient of elliptical boiler tube models and to predict the temperature distribution on optimized CFB boiler tube along the influences of constant temperatures. Additionally, to improve thermal performance of CFB boiler tube, and comparing the best configuration of optimized CFB boiler tubes model under the analysis of influencing parameters.

II. LITERATURE REVIEW

This section shows the study of different research paper related to the topic and draws some conclusion in terms of problem statement and also identified the literature gap of the literature and discusses the best methodology adopted.

Y. Chen et al. [9] experimentally determined the thermal-hydrodynamic performance of water-wall system based on the mass and energy equations using the measured temperature was calculated. The results showed that the temperature of the water-wall tubes increased as the furnace height increased, showing a positive response characteristic in the water-wall system. G. Song et al. [10] investigated the heat transfer uniformity of fluidized bed heat exchangers (FBHEs), a series of experimental tests were carried out in a commercial 300 MW CFB boiler. The test results indicate that there is a good linear correspondence between the FBHEs conical valve openings and circulating ash flow rate, the average heat transfer coefficient of different heat exchangers takes on a monotonically increasing trend with the increase of the boiler loads. Yuge yao et al. [11] studied a new method for tube-wall temperature measurement in CFB boilers. In this method, thermocouples are embedded on the heating surface in deposited metal and three different designs of deposition shapes were also provided. Results showed that the maximum values of temperature increase the measuring point under various working conditions in the three designs. Jaroslaw Krzywanski et al. [6] presented the key features of the fuzzy logic (FL) approach as a cost-effective technique in simulations of complex systems, and then demonstrate the formulation and application of the method. Hong Xu et al. [12] numerically evaluated the wall temperature profiles of the high temperature surface tubes in power plant using FVM. The model permits the consideration of oxide scales in the inner wall, which can leading to the overheating of material. The higher mass flow rate will increase the convection coefficient and decrease the heat flux from the tube metal to the steam. A. Blaszczuk et al. [13] focussed on the assessment of heat transfer impact of bed temperature on the local heat transfer characteristic between a fluidized bed and vertical rifled tubes (38mm-O.D.) in a commercial circulating fluidized bed (CFB) boiler. The heat transfer experiments were conducted for the active heat transfer surface in the form of membrane tube with a longitudinal fin at the tube crest under the normal operating conditions of CFB boiler. L. Xu et al. [4] proposed a method of combined thermal-hydraulics inside the water-wall tubes and thermal process on the furnace gas–solid side (HFW) for a detailed understanding of heat transfer characteristics on heating surface. The method consists of three main steps: 1. gas–solid hydrodynamic simulation by means of the Eulerian–Eulerian model; 2. bed-to- wall heat transfer coefficient calculation based on cluster renewal model; and 3. coupling thermal- hydraulic calculation at supercritical condition. P. Oclon et al. [14] this study presents a novel, simplified model for the time-efficient simulation of transient conjugate heat transfer in round tubes. The flow domain and the tube wall are modeled in 1D and 2D, respectively and empirical correlations are used to model the flow domain in 1D. The benefit of the proposed approach is that it can be applied to large systems of tubes as encountered in many practical applications. J. Taler et al. [15] suggested three different tubular type instruments (flux tubes) to identify steady-state boundary conditions in water wall tubes of steam boilers.

III. METHODOLOGY

To achieve the objectives of present research work, the flow chart of the action plan is shown in Figure 1.

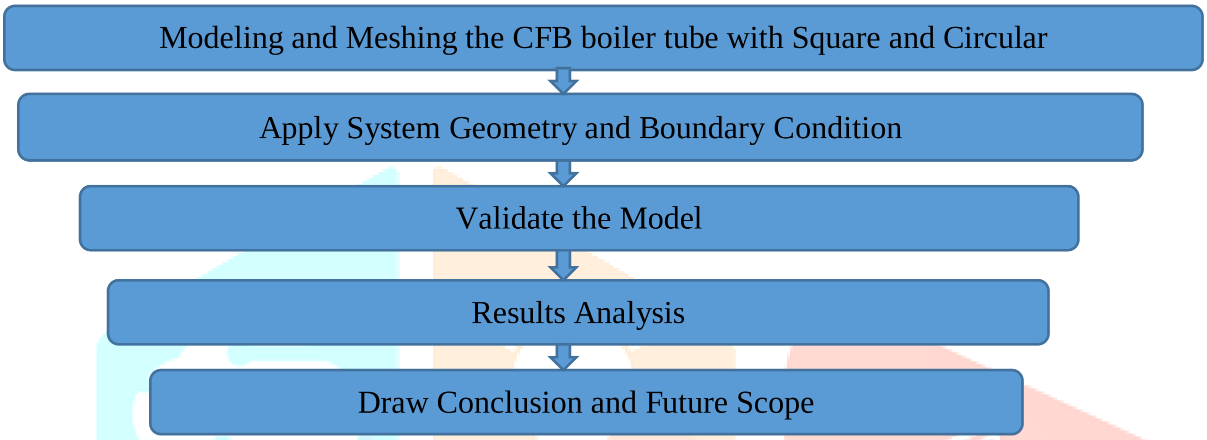

Fig 1. Flow Chart for Achieve desirable Objectives

IV MODELING AND MESH GENERATION

The dimensions of the computational domain of CFB boiler tube were based on the work done by Yuge Yao [11] author of base paper that was considered for present simulation of CFB boiler tube model. After this process the constraints were applied and this way the model was created in modelling software UNI -GRAPHICS NX-8.0 The following Table 2 show basic geometric parameters of CFB boiler tube.

Table 2 Basic Geometry Parameters of CFB Boiler Tubes

Geometric Parameter	**Value × 10^3**
Inner Diameter of the Tube (di)/m	38
Outer Diameter of the Tube (do)/m	50
Thickness of membrane fin (lm)/m	6
Tube Pitch (lp)/m	60
Thermocouple Diameter (dt)/m	2
Characteristics deposition thickness (ld)/m	1.5

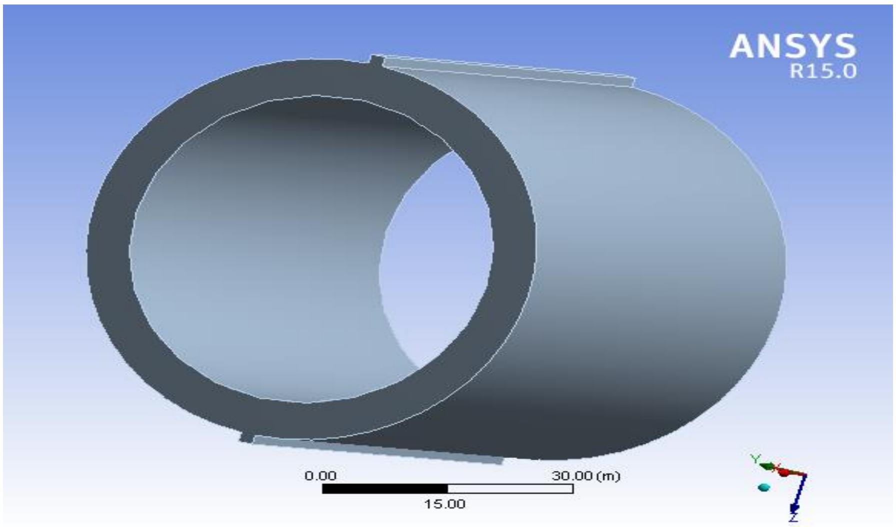

Fig 2. 3D model of CFB boiler tube with fin (Validation model)

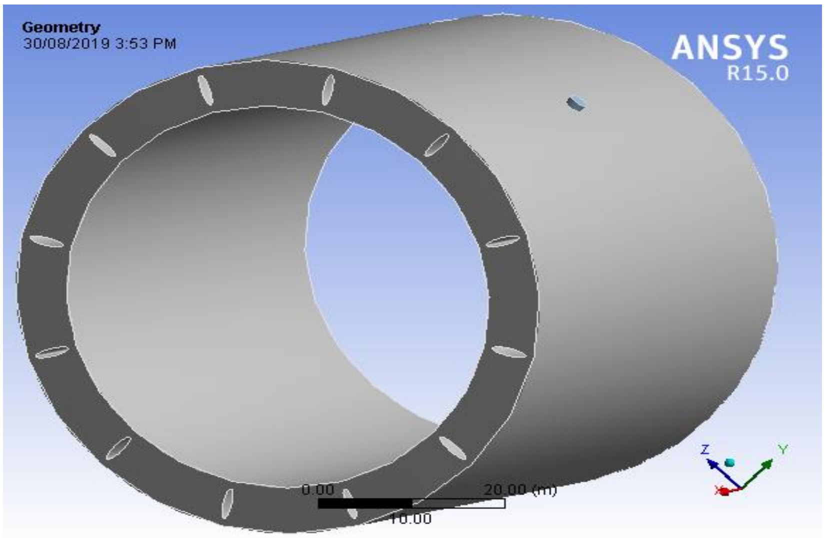

Fig. 3. 3D model of CFB boiler tube with elliptical shaped perforations

As above depicted figure 2 and 3 shows the three dimensional model CFB boiler tube for validation and elliptical shape respectively. The total number of elements of 58200 & nodes of 266169 were employed to assess the grid independence in the CFB boiler tube case. The total number of elements higher than above mesh was employed in the CFB boiler tube (Elliptical perforation) case. It is clear that the present results have good agreement with the available data in the literature. The results of the grid refinement study showed that the simulation based on the CFB boiler tube case and CFB boiler tube (Elliptical perforation) case mesh provide satisfactory numerical accuracy, and are the essentially grid independent in this case.

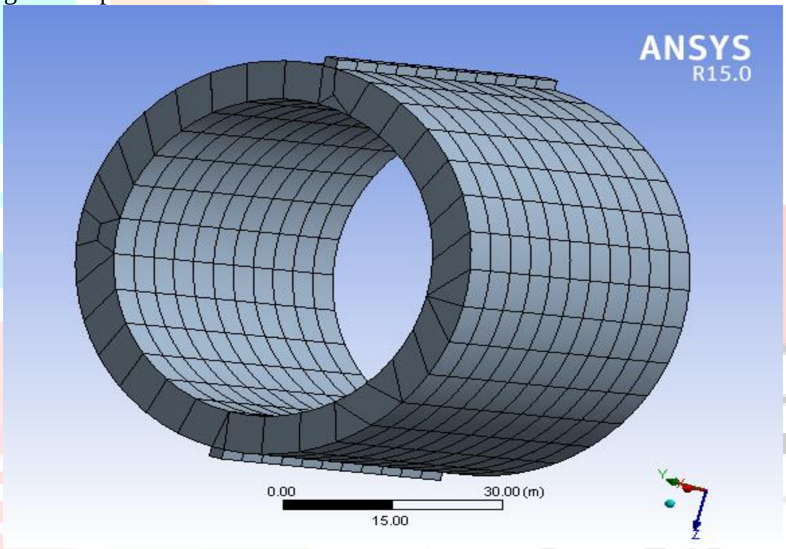

Fig.4. Mesh of CFB boiler tube with fin (Validation model)

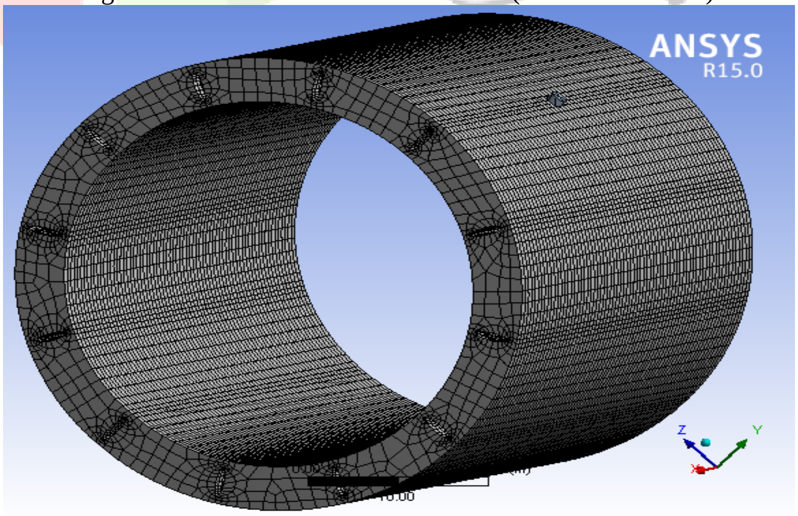

Fig. 5. Mesh of CFB boiler tube with elliptical shaped perforations

As above depicted figures 4 and 5 shows the meshing of three dimensional model CFB boiler tube for validation, square shape, circulating shape and elliptical shape respectively.

4.1 Boundary Condition

Given the periodic structure of the CFB boiler tube, the two thermal parameter is investigated. Thermal domain employed. The material of the CFB boiler tube is 15crmo. The circumference of inside tube is heated at a constant heat transfer rate of 873K that is the and at different profiles of CFB boiler tube i.e. tube with square, circular, elliptical perforations. The temperature is assumed to be constant Radiation effect is ignored.

4.2 Governing Equation

The governing equations in the form of continuity, momentum and energy are shown below [14, 16]. The continuity equation is written as

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \qquad (1)$$

The momentum equation is written as

$$\frac{\partial(\rho\overline{u_i u_j})}{\partial(x_j)} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right) - \frac{\partial(\overline{u_i{}'u_j{}'})}{\partial x_j} \qquad (2)$$

The energy equation is represented as

$$\frac{\partial}{\partial x_i}\left(u_j(\rho e + p)\right) = \frac{\partial}{\partial x_j}(\lambda\frac{\partial T}{\partial x_j}) \qquad (3)$$

where p is pressure, ρ is the fluid density, T is fluid temperature, λ is thermal conductivity and μ is fluid viscosity respectively. The Re-Normalisation Group (RNG) version of k-ε model is used in this numerical study. The Turbulent kinetic energy k is

$$\frac{\partial}{\partial x_j}\left(\rho k u_j\right) = \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_t}{\sigma_k}\right)\lambda\frac{\partial k}{\partial x_j}\right) + G_k - \rho\varepsilon \qquad (4)$$

V RESULT AND DISCUSSION

The three-dimensional models of different CFB boiler tube are developed to investigate thermal performance in the (perforation in tube) CFB boiler tube for temperature distributions. A series of numerical calculations have been conducted using steady state thermal domain and the results are presented in order to show the effects of temperature distribution and heat transfer coefficients CFB boiler tube profiles. The validation of the results is done by carrying out the simulations work on the CFB boiler tube using ANSYS on steady state thermal domain 15.0 Workbench. This work has been validated by Yuge Yao et al. [11]. To determine the validation graphs and data evaluated using formulas for convergence between temperature and heat transfer coefficients with respect to constant temperatures.

5.1 Simulation Results for Different Configurations of CFB boiler tube Models

The Existing simulation results are obtained for temperature distribution and heat transfer coefficients, constant temperature ranging from 673K to 873K. The results are in graphs show less than 15% deviations between existing simulation results. But the deviations are not so large, and thus the existing simulation results of elliptical configurations of different CFB boiler tube models in the research work can be regarded as considerable. The figure 6 shows that the temperature distribution of CFB boiler tube with fin (validation model) and also the heat temperature co-efficient shown in the figure 7.

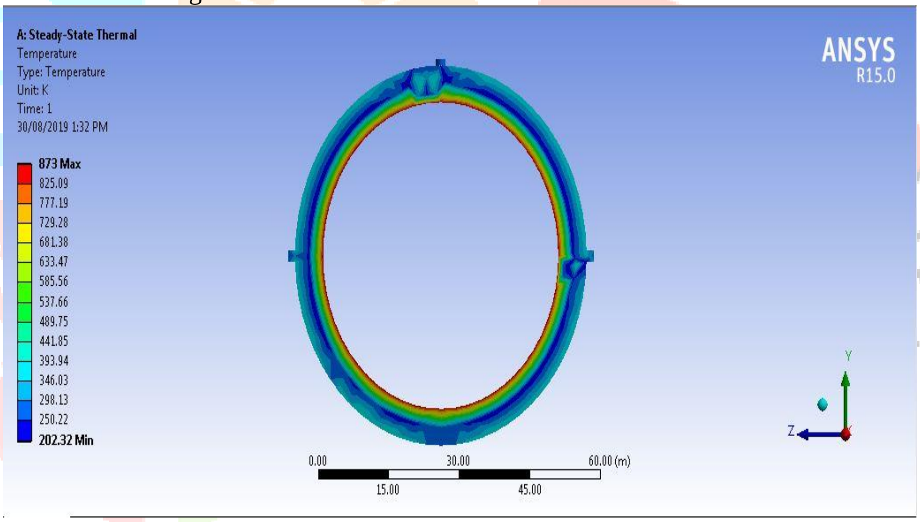

Fig. 6 Temperature distribution of CFB boiler tube with fin (Validation model)

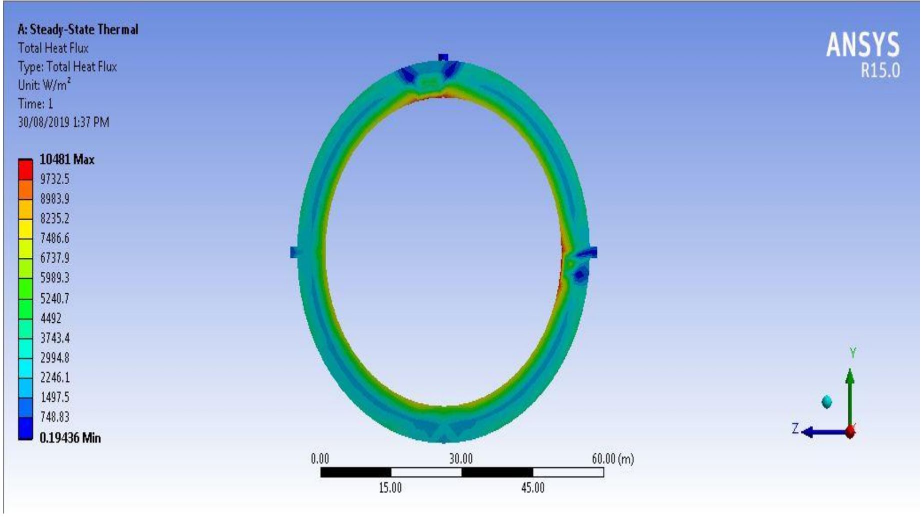

Fig. 7. Heat Transfer Coefficient of CFB boiler tube with fin (Validation model)

Table 3 Temperature distribution and heat transfer coefficient in CFB boiler tube with fin (Validation model)

Validation			
Heat Flux	**Tf=673K**	**Tf= 773**	**Tf=873**
1000	4.4	3.5	2.4
1500	3.3	2.6	1.9
2000	2.7	2.1	1.5
2500	2.2	1.7	1.2
3500	1.9	1.3	0.9

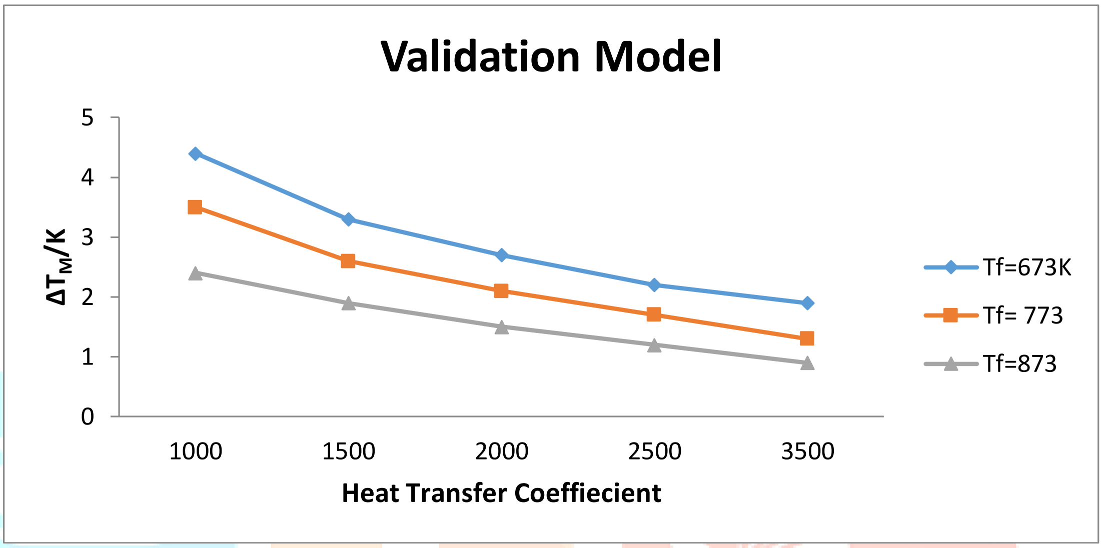

Fig.8. Temperature distribution and heat transfer coefficient in CFB boiler tube with fin (Validation model)

The table 3 shows the temperature distribution and heat co-efficient value in CFB boiler tube with fin (validation model) at value of Tf = (673K), Tf = (773K), and Tf = (873K). As above depicted figure 8 shows that temperature distribution and heat co-efficient value in CFB boiler tube with fin (validation model) at value of Tf = (673K), Tf = (773K), and Tf = (873K). The difference in temperature constant heating power 873K, thermal resistance decreases and by these effects of heat transfer coefficient increases.

Table 4 Temperature distribution and thermal conductivities in CFB boiler tube with fin (Validation model)

Validation			
Thermal Conductivities	**Tf=673K**	**Tf= 773**	**Tf=873**
24.33	3.6	2.9	1.9
23.38	2.5	2.1	1.2
22.34	1.9	1.3	0.9
21.48	1.4	0.9	0.6
20.4	1.1	0.6	0.4

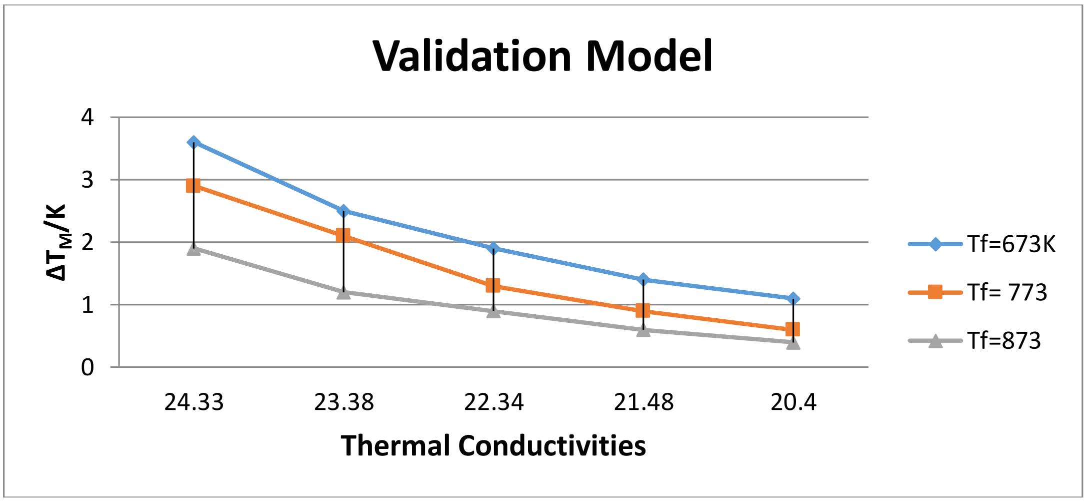

Fig. 9 Temperature distribution and thermal conductivities in CFB boiler tube with fin (Validation model)

As per above depicted table 4 shows that temperature distribution and thermal conductivity value in CFB boiler tube with fin (validation model) at value of Tf = (673K), Tf = (773K), and Tf = (873K). As above depicted figure 9 shows that temperature distribution and thermal conductivity value in CFB boiler tube with fin (validation model) at value of Tf = (673K), Tf = (773K), and Tf = (873K) and perforation in circumference of tube of deposited material the effect of thermal conductivity at 673K of constant temperature enhances maximum temperature distribution in tube wall.

5.2 Optimization Results Analysis of Temperature Distribution with Heat Transfer Coefficient of CFB boiler tube with Elliptical Perforations

The elliptical shaped perforation of CFB boiler tube models are simulated and optimization results of temperature distribution, heat transfer coefficient at constant operating temperatures are presented in figure 10 and 11 below.

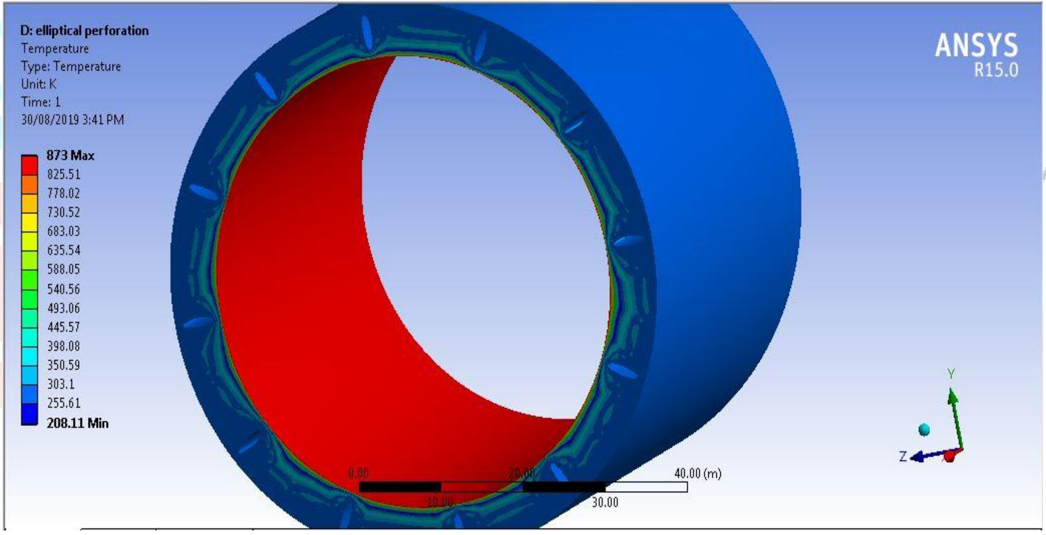

Fig. 10 Temperature distributions in CFB boiler tube with elliptical shaped perforations

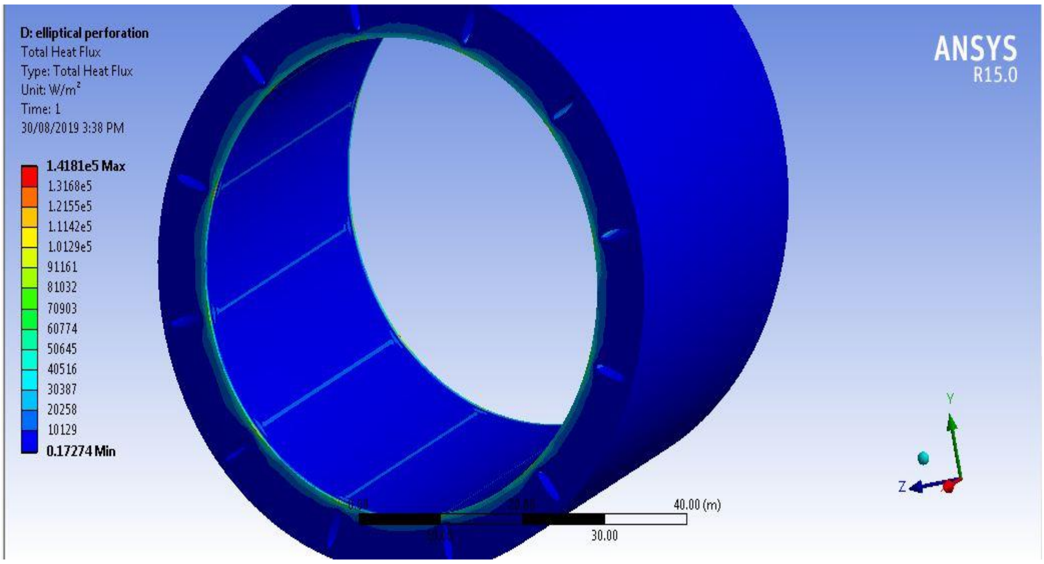

Fig. 11 Heat flux distribution CFB boiler tube with elliptical shaped perforations

Table 5 Temperature distribution and heat transfer coefficients in CFB boiler tube with elliptical shaped perforations

Elliptical Perforation			
Heat Transfer Co-efficient	Tf=673K	Tf= 773	Tf=873
2000	3.6	2.9	1.9
4231	2.5	2.1	1.2
6879	1.9	1.3	0.9
8465	1.4	0.9	0.6
10129	1.1	0.6	0.4

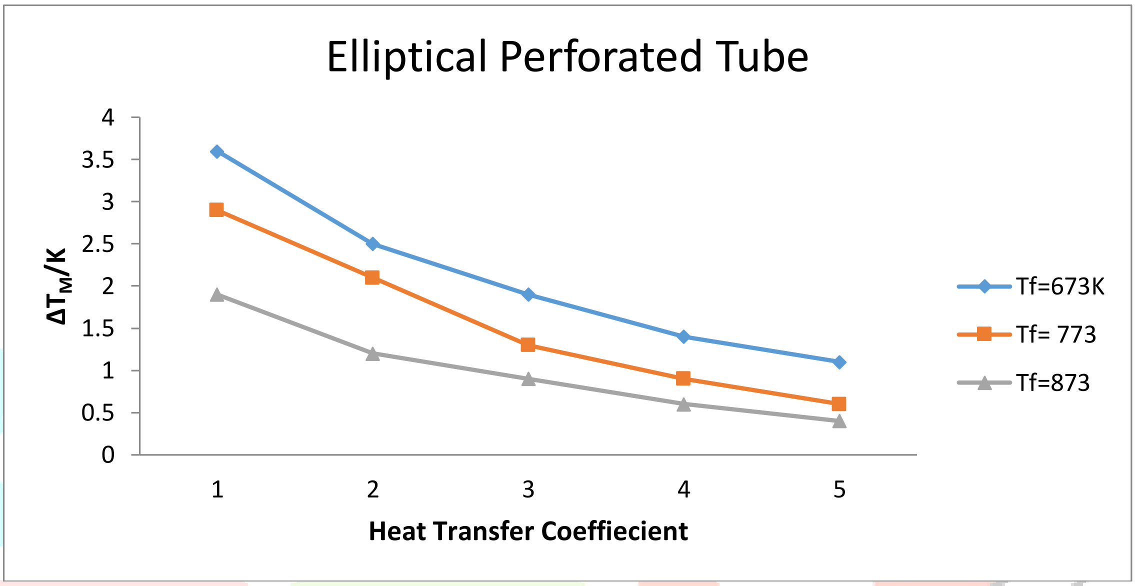

Fig. 12 Temperature distribution and heat transfer coefficients in CFB boiler tube with elliptical shaped perforations

As per above depicted table 5 shows that temperature distribution and heat co-efficient value in CFB boiler tube with fin (elliptical perforated tube) at value of Tf = (673K), Tf = (773K), and Tf = (873K). As above depicted figure 12 shows that temperature distribution and heat co-efficient value in CFB boiler tube with fin (elliptical perforated tube) at value of Tf = (673K), Tf = (773K), and Tf = (873K) and concluded The difference in temperature constant heating power 873K, thermal resistance decreases and by these effects of heat transfer coefficient increases.

Table 6 Temperature distribution and thermal conductivities in CFB boiler tube with elliptical shaped perforations

Elliptical perforation			
Thermal Conductivities	**Tf=673K**	**Tf= 773**	**Tf=873**
24.33	4.4	3.5	2.4
23.38	3.3	2.6	1.9
22.34	2.7	2.1	1.5
21.48	2.2	1.7	1.2
20.4	1.9	1.3	0.9

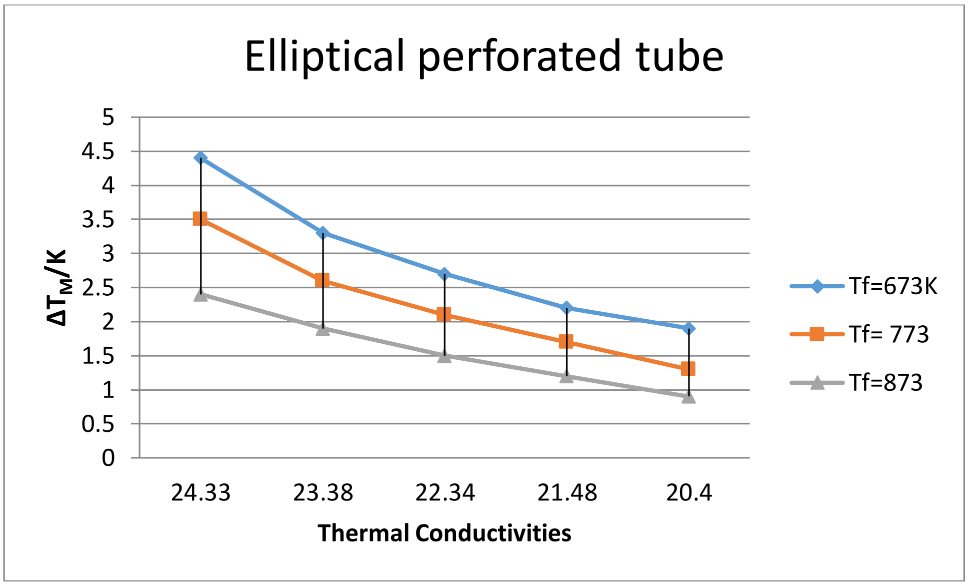

Fig. 13 Temperature distribution and thermal conductivities in CFB boiler tube with elliptical shaped perforations

As per above depicted table 6 shows that temperature distribution and thermal conductivity value in CFB boiler tube with fin (elliptical perforated tube) at value of Tf = (673K), Tf = (773K), and Tf = (873K). As above depicted figure 13 shows that temperature distribution and thermal conductivity value in CFB boiler tube with fin (elliptical perforated tube) at value of Tf = (673K), Tf = (773K), and Tf = (873K) and perforation in circumference of tube of deposited material the effect of thermal conductivity at 673K of constant temperature enhances maximum temperature distribution in tube wall.

VI. CONCLUSION

In this research, detailed analysis of the influences of temperature distribution, heat transfer coefficient and thermal conductivity of CFB boiler tube with different profiles has been conducted by simulations using the ANSYS software on steady state thermal domain 15.0. Work bench. The following conclusions are withdrawn:

- The temperature distribution is the fundamental parameter in the performance of CFB boiler tube. The tube surface area of elliptical shows that the thermal resistance effect is observed to decrease significantly.
- In the study, CFB boiler tube i.e. tube with elliptical perforations is a key geometric parameter on the performance of CFB boiler tube. With an implementation of elliptical perforation in circumference of tube of deposited material the effect of thermal conductivity at 673K of constant temperature enhances maximum temperature distribution in tube wall.
- The proposed types of CFB boiler tube represented on results show that perforation increases surface area, and decreases the thermal barriers due to it can recognize that elliptical shaped perforation is the best configuration.
- The simulations of CFD models of CFB boiler tube with different configurations show a good relation with base paper results presented in the literature.

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