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Numerical Investigation of the Effect of Different Conical Turbulators on the Performance of a Liquid Fuelled Boiler

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Abstract
The increment in the combustion of fossil fuels for heating and power generation in recent years has led researchers to design more efficient energy conversion systems by increasing the efficiency of the existing systems and by minimizing energy losses. In this study, increasing the efficiency of the liquid fuelled smoke tube boilers used for domestic heating was researched. In this context, turbulators with full conical and frusto-conical geometries placed to smoke tubes of boiler and their effects on flame structure, heat transfer and boiler efficiency were investigated numerically. Calculations were carried out at two dimensional axisymmetric conditions and Fluent was used as the computational fluid dynamics software. In all cases, the standard k-ε model was used for modelling the turbulent flow and the species transport model was used for modelling the combustion. The results obtained by using these turbulators were evaluated for each placement condition of the turbulators. Besides, the temperature and the stream function distribution and the pressure drop in the boiler were investigated according to the type of turbulators. Finally, it was discussed which type of turbulator would be most appropriate at boilers.
Keywords: Spray Combustion; Combustion Modelling; Boilers; Conical Turbulators

1. Introduction

The importance of the production and the efficiently usage of energy increases day by day with the world population increment. Especially, in recent years various methods have been developed to save energy in the energy sector. Heat exchangers are one of the areas in which energy savings are made. Smoke tube boilers are also a heat exchanger used for heating purposes. To enhance heat transfer in the heat exchangers, it is possible to classify the methods as active and passive. If heat transfer happens with additional power to the fluid or environment which provides improvements in heat transfer, it is called active method, and if heat transfer happens without additional power, it is called passive method. To increase the heat transfer, increment of the surfaces increases the heat transfer. But with increasing surface, volume of the heat exchanger is growing. To prevent this, a turbulator to be inserted into the heat exchanger provides an increase on the heat transfer surface area and the heat exchangers volume will remain stationary. The turbulators placed into the pipe increase turbulence in the flow and subsequently improve the heat transfer. In other words, turbulators are devices which improve the heat transfer between fluids at different temperatures. In the installed systems, increasing the efficiency of the existing system with passive heat transfer methods (demountable turbulators) is preferred rather than rebuilds the entire system for heat exchangers or change necessary equipment's with new one. Thus, these devices, which are unlikely to be used for other systems can be used again and manufacturing companies will have the opportunity to sell their products for a cheaper price and with a better quality.

Many researchers have tried to understand the heat transfer effects of turbulators which are inserted in the pipes. Muthusamy et al. (2013) investigated the heat transfer, friction factor and thermal performance of conical turbulators with inner fins on flow direction and on the opposite flow direction experimentally. They stated that the turbulators inserted on the flow direction had better heat transfer results. Yakut and Sahin (2004) investigated experimentally the effect of coiled wire turbulators inserted to the tubes on the heat transfer and friction factor. Akansu (2006) analysed numerically the effect of turbulators like porous-ring shaped to heat transfer and pressure drop. He used Fluent software in calculations. He used k-ω model as turbulence model and air as a fluid. Kareem et al. (2015) investigated the heat transfer effects in three-start spirally corrugated tube experimentally and numerically. Anvari et al. (2014) studied experimentally and numerically to find the role of the conical rings for the heat transfer enhancement and pressure drop change in a pipe. Durmuş et al. (2004) were investigated experimentally the effects of propeller-type turbulators with different blade angles which were inserted to the pipe of heat exchanger.

Some studies with numerical modelling of the spray combustion were investigated by many researchers. Saario et al. (2005) investigated the heavy fuel oil combustion in the furnace experimentally and numerically. For numerical simulation they used Fluent software and they used standard k-ε and Reynolds Stress Model (RSM) separately as turbulence model. The mixture fraction approach and the probability density function approach were used as combustion model. They said that predicted gas concentrations were in satisfactory agreement with measurement results, but they found that there were conflicting results near the burner and near the furnace axis. Furuhata et al. (1997) examined the performance of numerical spray combustion simulation of heavy oil. They used Lagrangian method for modelling the fuel droplets behavior. Mondal and Roy (2006) investigated the liquid droplets of Toluene burning characteristics for different combustor geometries and droplet sizes. Nieckele et al. (2010) examined the combustion performance of an aluminium melting furnace operating with liquid fuel. They used Fluent software in numerical solutions.

In this study, a liquid fuelled flame tube boiler was modelled at two-dimensional conditions for ten different geometries including the basic geometry without turbulator. The effect of full and frusto-conical turbulators and their combinations (combined conical) with various numbers which were inserted to smoke tubes to heat transfer were investigated numerically. Both type of turbulators used in the calculations are 75 mm long, 60 mm diameter and 0.8 mm wall thickness. For both types and combined type, turbulators inside the smoke tubes were placed as ace, double, triple.

2. Materials and Methods

Computational Fluid Dynamics (CFD) is a field of fluid mechanics, which solves the problems related to heat transfer, fluid motion, particle motion, droplet motion and combustion with numerical methods and algorithms via a computer. In recent years, developments on the technology and computer science have increased the importance of CFD software. Using physical experiments to get essential engineering data for design can be expensive and time consuming. CFD simulations are relatively cheap and can be executed in a short period of time compared to experiments. Currently, there are various commercial CFD codes in the market and FLUENT software is one of them.

Modelling of the movement of the gas phase was made by Eulerian perspective to solve the mass, momentum, and energy conservation equations for scalar variables. These differential equations were solved using appropriate boundary conditions on the problem. The general form of the steady state governing equations (continuity, momentum, energy and species) for the 2D turbulent reactive flow under cylindrical coordinates is expressed as follows:

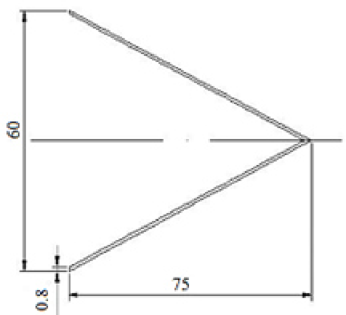
$$\frac{\partial}{\partial x}(\rho u\phi)+\frac{1}{r}\frac{\partial}{\partial r}(r\rho v\phi)=\frac{\partial}{\partial x}\left(\Gamma\frac{\partial\phi}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma\frac{\partial\phi}{\partial r}\right)+S_{\phi} \quad (1)$$

where ϕ denotes 1, u, v, k, ε, h, Y_i and the general diffusion coefficient Γ is in turn 0, μ_t

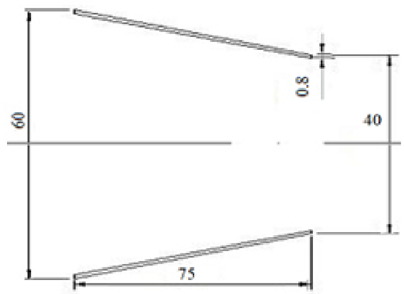
, μ_t , $\frac{\mu_{eff}}{\sigma_k}$, $\frac{\mu_{eff}}{\sigma_\varepsilon}$, $\frac{\lambda}{c_p}+\frac{\mu_t}{\sigma_h}$ and $\rho D_{im}+\frac{\mu_t}{\sigma_Y}$, respectively.

Lagrange perspective was used for modelling of the movement of the liquid phase. Fuel was sprayed by the pump into combustion air delivered by a fan or compressor. Different velocity and droplet size were formed as a result of spraying. Due to different initial values, droplets tracked on different trajectories, heat and evaporate with different velocities, then mixed with air and burn. For the determination of droplet spectrum, Fluent offers dispersion models such as linear dispersion, and Rosin Rammler dispersion models (Fluent, 2006). The motion of the gas and liquid phases were taken into account with successive iterations.

For the numerical modelling of the combustion, it is necessary to define combustion model, turbulence model and radiation model. In this study, the species transport-eddy dissipation model was used as combustion model, the standard k-ε model was used as turbulence model, and P1 approach model was used as radiation model. Liquid fuel was injected from the center of the burner. The full and frusto-conical turbulators which were inserted to smoke tubes were shown in Fig. 1. Calculations were carried out for ten different situations with Geometry 1, which presents the basic geometry without turbulator; Geometry 2 presents the one with full conical turbulators; Geometry 3 presents the frusto-conical turbulators; and Geometry 4 presents the combination of full and frusto-conical turbulators. The numbers coming after the geometry numbers show the number of turbulators in smoke tubes. These geometries were given in Fig. 2. Only one half of the smoke tube geometries with turbulators are shown because of the axial symmetry. Injector spray pressures were adjusted to 8 bars. Group injection model was used as the injection type, the injection half angle was given 30° and the injector diameter was given 0.4 mm. Rosin-Rammler dispersion model was used for modelling the dispersion of droplets. $C_{10}H_{22}$ fuel was accepted as diesel fuel and the fuel viscosity was entered 0.0024 kg/m s.



(a)



(b)

Figure 1. Dimensions of the turbulators; a) conical turbulator, b) frusto-conical turbulator

Schematic diagram of the reverse flame fire tube boiler was given in Figure 3. The mesh structure of Geometry 1 was given in Figure 4. This mesh had a total of approximately 230,000 cells. Also, more grid structures were tested to see the grid's effect on the solution. Both fine grid and coarser grid were used for calculations. However, in these calculations with more grids, there were no meaningful changes in the results. The other geometries (Geometry 2-1, Geometry 2-2 and Geometry 2-3) had almost the same mesh sizes and all calculations were performed with the grid having 230,000 meshes. All surfaces in contact with water were defined as the wall having temperature of 353 K. Exit zone was defined by the pressure outlet, and air inlet was defined by velocity inlet.

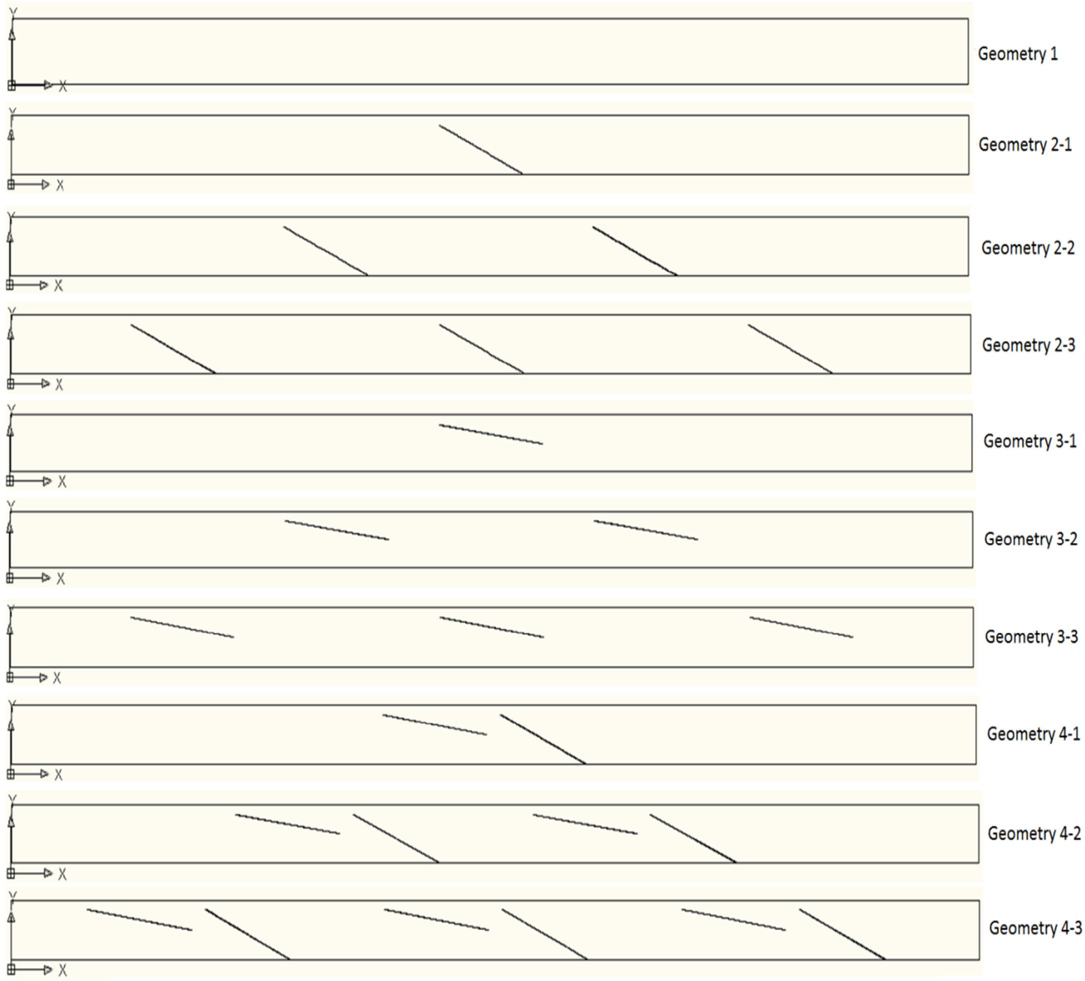


Figure 2. Different number of turbulators inserted to the smoke tubes

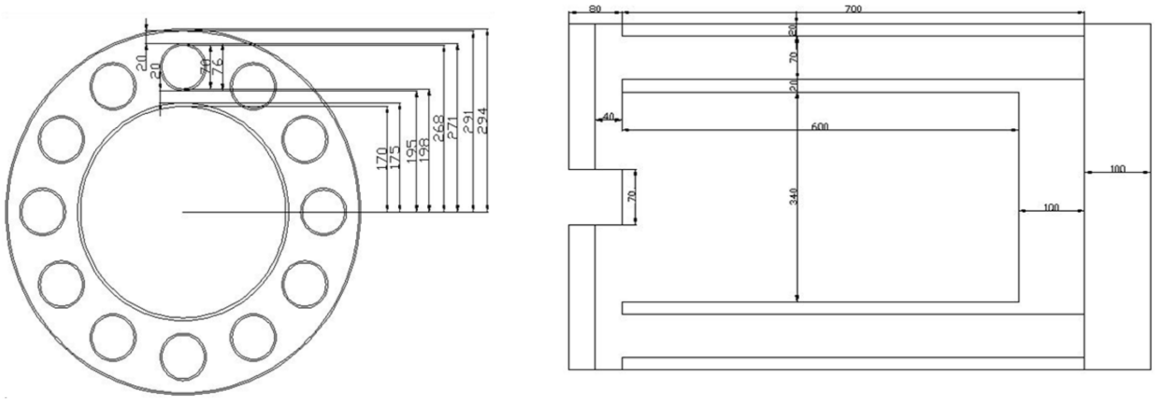


Figure 3. Schematic diagram of the boiler

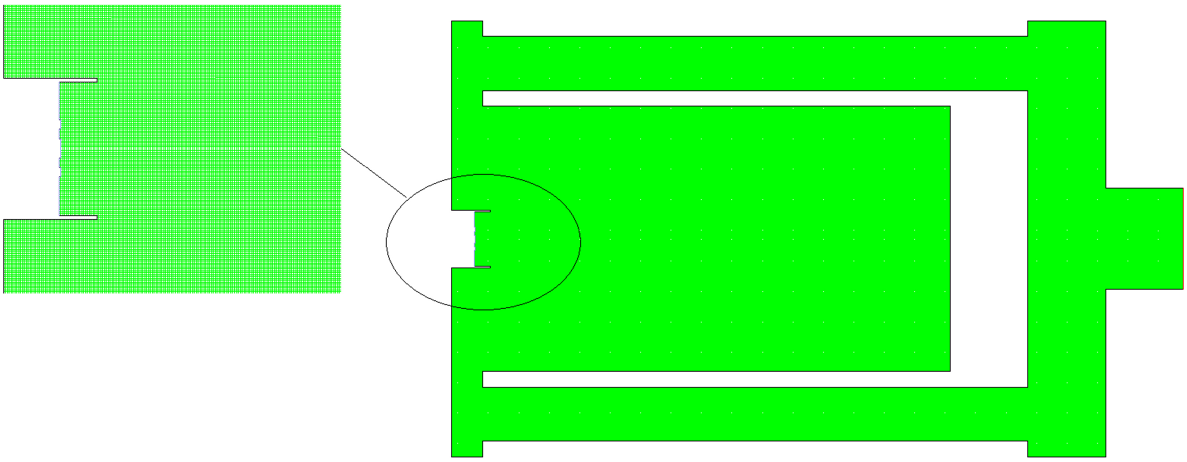


Figure 4. The mesh structure of the solution domain

4. Results and Discussion

Figure 5 represents the droplet trajectories. As shown in this figure, the maximum droplet diameter was 100 µm and the minimum droplet diameter was 5 µm. The droplets dispersed in the gas flow according to injection conditions with an half angle of up to 30 degree. Their trajectories remained fairly straight and were not influenced much from the gas phase flow. The smaller droplets warmed up, evaporated and burned very fast. The bigger droplets, on the contrary, needed more time for the same processes. Only the droplet trajectories of the Geometry 1 were shown because the droplets behaviour was similar at all solutions.

The flame formed after the fuel injection in the combustion chamber had three passes. The first pass was the flame itself near the axis, the second was the pass backwards from the rear end of the combustion chamber to the front (reverse flame) and the flue gas flow through the smoke tubes was the last pass. Figure 6 shows the temperature contours in the boiler for ten different situations. From this figure it can be said that, temperature decreased along the flame tube and smoke tube due to the flame tube and smoke tubes surrounded with water; because the heat of combustion was transferred to these regions. Frusto-conical turbulators showed similar results with basic geometry. The combined turbulators showed similar results with conical turbulators. As shown in this figure, the minimum heat transfer was realized with Geometry 1. When examined the group of Geometry 2 itself, it can be seen that increasing the number of turbulators increases the heat transfer. The same can be said for Geometry 4. Geometry 3 has not a considerable positive effect on the heat transfer in relation to Geometry 1 and increasing the number of turbulators do not change this situation remarkably. In all cases, the flame structure in flame tubes has not been influenced essentially.

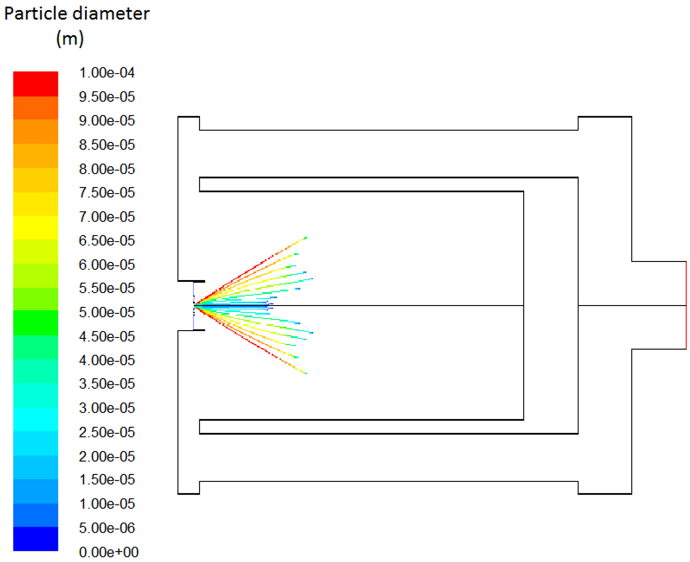


Figure 5. Droplet trajectories in the boiler

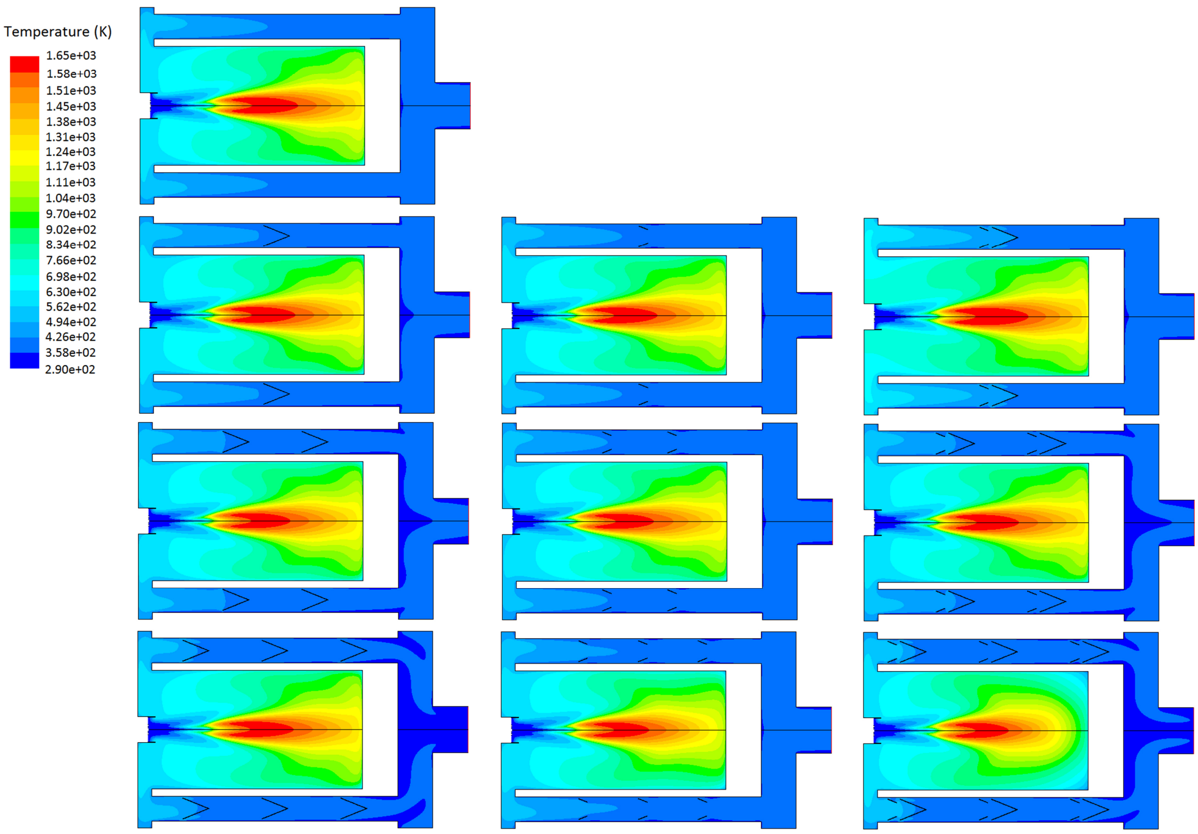


Figure 6. The temperature contours in the boiler for different insertion geometries

Stream functions of the flow in the boiler were given in Fig. 7. It can be seen from this figure that eddies occurred in front and rear of the turbulators in the smoke tubes with the use of turbulators. Eddies improve the mixing and consequently the heat transfer. In the group of Geometry 2 and Geometry 4, it was shown that eddies increased with increasing number of turbulators. However, in the group of Geometry 3 almost none eddies occurred and this situation has a negative effect on heat transfer compared to Geometry 2 and Geometry 4.

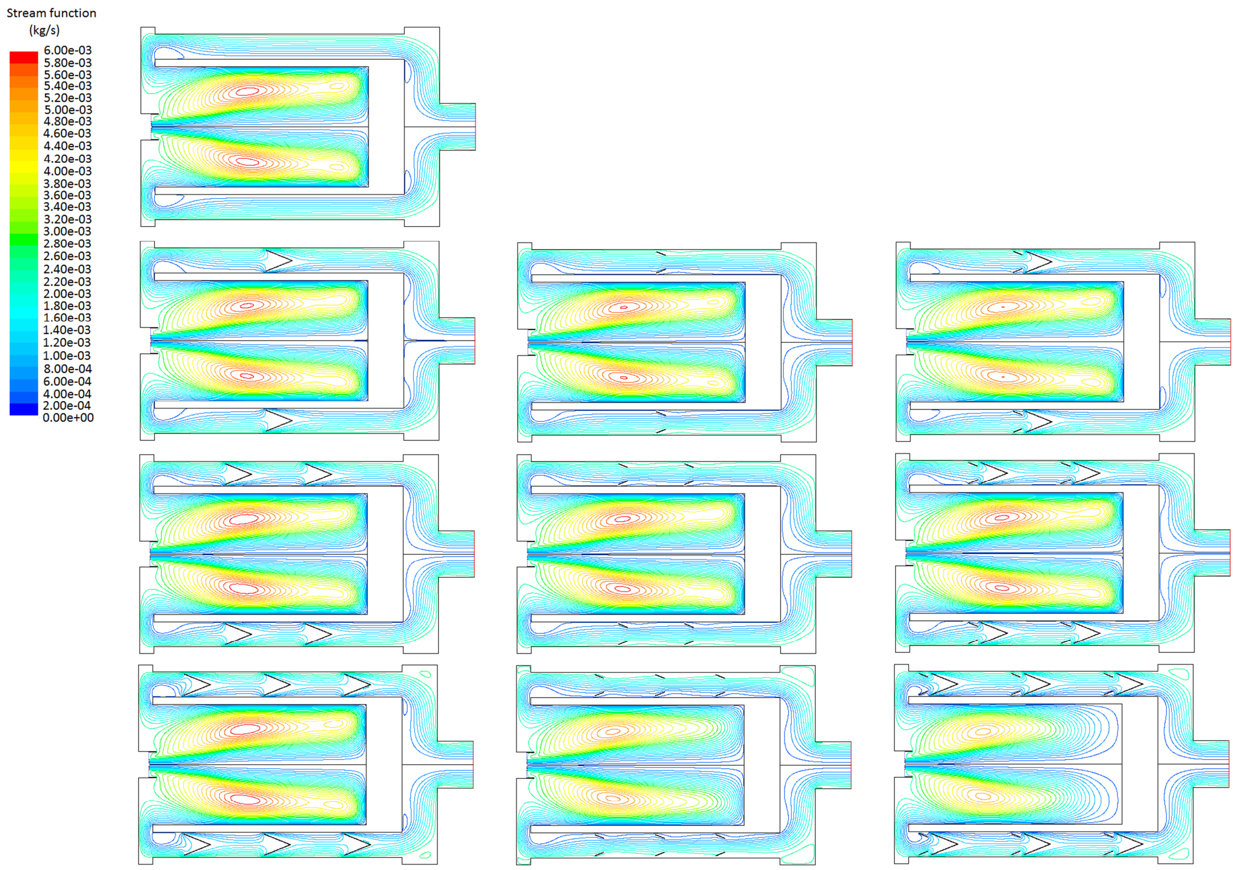


Figure 7. Stream functions in the boiler for different insertion geometries

To improve the thermal efficiency, the sensible heat of flue gases must be diminished, accordingly the exhaust gas temperature must be decreased. Exhaust gas temperatures for ten different insertion geometries were given in Figure 8. Exhaust gas temperatures decreased slightly with increasing number of full and combined conical turbulators in smoke tube. As mentioned before, frusto-conical turbulators has almost none effect on flow and as shown in this figure it has slightly lower exhaust temperature results than Geometry 1, but increasing the number of frusto-conical turbulators did not change the results. Geometry 1 had the maximum exhaust temperature which was 365 K. Geometry 2 (full conical) and Geometry 4 (combined conical) had similar exhaust temperature results and in these geometries increasing the number of turbulators decreased the exhaust temperatures. The minimum exhaust temperature was obtained with Geometry 4-3 (3 full conical+3 frusto-conical) and the temperature difference between Geometry 1 and Geometry 4-3 was almost 16 °C.

Comparison of the pressure losses were given in Figure 9. As can be seen from this figure, increasing the number of full and combined conical turbulators increased the pressure losses. Geometry 3 has almost none effect on pressure losses like other results. Geometry 2 and Geometry 4 had similar results and Geometry 4-3 had the maximum pressure loss with 23.7 Pa.

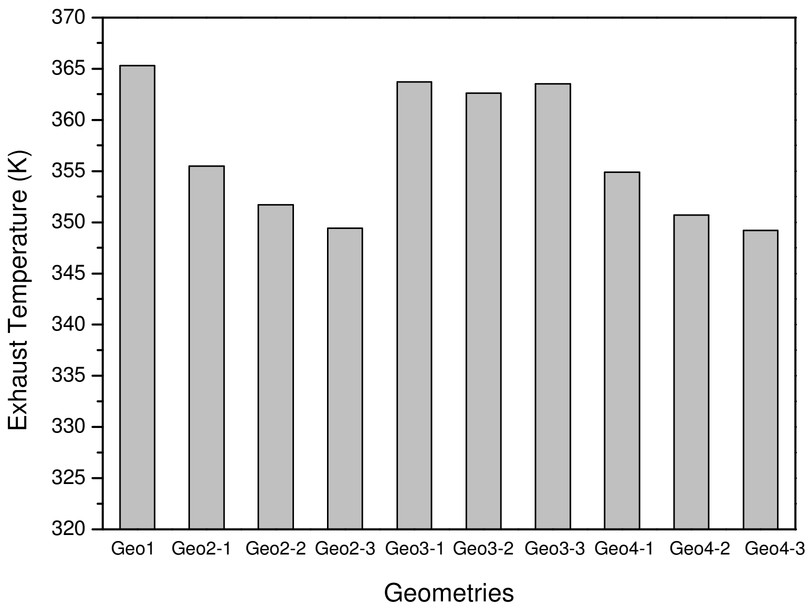


Figure 8. Comparison of the exhaust temperatures for the different insertion geometries

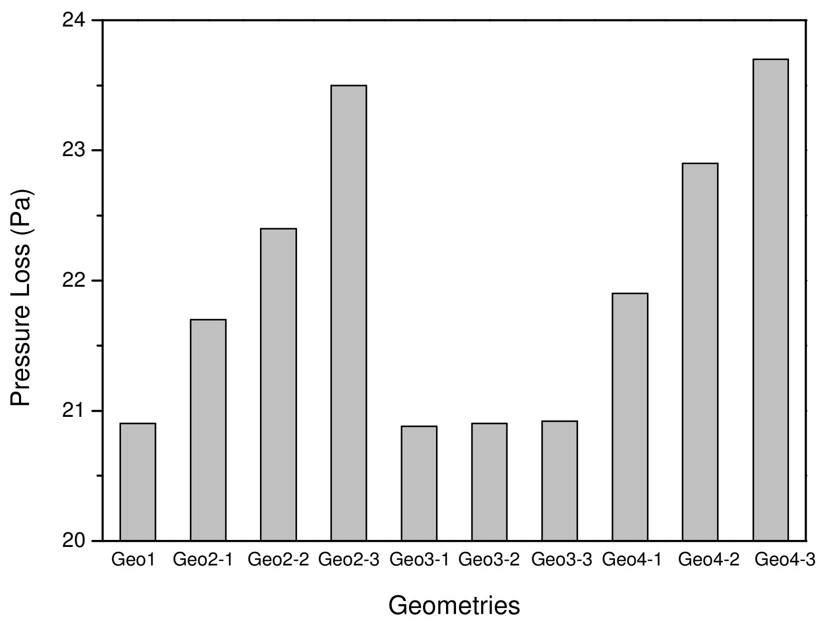


Figure 9. Comparison of the pressure losses for the different insertion geometries

5. Conclusions

In this study, a liquid fuelled flame tube boiler having different type conical turbulators was modelled at two-dimensional conditions with ten different geometrical insertions. With increasing number of full and combined conical turbulators, which were inserted to smoke tubes, the exhaust gas temperatures decreased and consequently the efficiency of the boiler was increased. This led on the other hand to higher pressure losses. The results of Geometry 2 and Geometry 4 were very close to each other. Geometry 3 (frusto-conical) has almost no influence on flow, heat transfer and pressure loss. Nevertheless, Geometry 4-3 had the best performance among all insertion geometries. The results obtained in this paper may provide significant guidance for the design of turbulators and the efficiency improvements of the flame tube boilers.

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