Numerical Investigation of the Effects of Gas Flow Passes on Performance of a Pellet Fuelled Boiler

B. Sungur and B. Topaloglu*

Abstract—**Biomass is a renewable and environmentally friendly energy source and readily available for heating and power generation applications. The main objective of this study is to investigate numerically the effects of the gas flow passes of a boiler (two and four passes) on combustion characteristics of pellet fuel in a smoke tube boiler at 30 kW loading conditions. As a Computational Fluid Dynamic (CFD) program Fluent package program was used. Calculations were performed at three dimensional conditions. According to the boiler geometry, temperature contours, velocity vectors, exhaust gas temperatures and efficiencies were investigated and results were discussed. The results showed that, the flue gas temperature of the four-pass boiler is about 50 K lower than the two pass boiler and the thermal efficiency is about 4% better. This study has provided valuable information for boiler manufacturers that can be used to help to improve future furnace design.**

Keywords— **Biofuels, Numerical modeling, Pellet, Pellet boilers**

I. INTRODUCTION

In recent years, saving energy and studies on the renewable energy resources is gaining importance day by day in the face of declining fossil-based resources. According to the sources, the distribution of energy consumption performed by taking the average of the last 5 years (2011-2015), the highest consumption is oil with 33% and it is followed by coal (30%), natural gas (24%), hydraulic (7%), nuclear (4%) and other renewable sources (2%), respectively [1]. Biomass which is one of the renewable energy sources becoming an important fuel recently. The economically and environmentally favorable properties of biomass fuels are one of the reasons why this renewable resource is preferred. Boilers can be defined as closed vessels in which combustion occurs and heat from combustion is transferred to a fluid. In general, boilers are used for heating purposes in houses and in many industries which require energy. The energy efficiency of boilers is dependent on combustion quality and amount of the combustion energy transferred to the fluid. However, flue gas emissions dependent on combustion quality, grate type, the amount of the contaminants in the fuel and operating conditions of the combustion system.

Pellet fuels are one of the biomass energy sources and are produced from sawdust, wood chips, bark, waste, agricultural products, stems of crops, hazelnut, almond and walnut shells etc. These materials, firstly grinded and then compressed under high pressure and typically 6-8 mm in diameter, 10-11 mm in length, with a cylindrical form. Pellet fuel is a sustainable resource and has many advantages like reducing fossil fuel imports, contributing to the economy, leaving less waste after usage, and leading to exhaust emissions within acceptable limits.

Literature survey carried out on the numerical modeling of the combustion of solid fuel boilers. Begum et al. [2] searched experimentally and numerically the fluidized bed gasification of solid waste. They carried out their experiments on a pilot scale gasifier and used Advanced System for Process Engineering (Aspen) Plus software for numerical calculations. They stated that experimental and numerical methods were in good agreement and said that the model could be useful to predict the temperature, pressure, air-fuel ratio and steam-fuel ratio of a gasification plant. Porteiro et al. [3] numerically analyzed the 24 kW pellet boiler in their work. They used k-ε model for modeling the turbulence, Discrete Ordinate (DO) model for modeling the radiation and Arrhenius Finite rate/Eddy dissipation model for modeling the gas phase. They presumed that biomass volatiles consist of CO, CO_2, H_2O, H_2, light hydrocarbons (CH_4) and heavy hydrocarbons (C_6H_6). They compared the gas temperatures and concentrations with numerical and experimental methods and stated that the results were in satisfactory agreement. Chaney et al. [4] investigated the combustion performance and NO_x emissions optimization of 50 kW pellet boiler. They said that there are many parameters which can improve the combustion performance and NO_x emissions like primary and secondary air adjustment, secondary air inlet number etc. For modeling the gas phase they used Eddy Dissipation model and as a CFD program they used Fluent program in their calculations. Collazo et al. [5] simulated the domestic pellet boiler with CFD program and they used Finite rate/Eddy dissipation model for modeling the gas phase. They stated that the numerical results were in good agreement with the experimental results. As a result of the boiler analyses they specified that the positions of water tubes and air inlet distributions were important factors which can cause the high emissions in such systems. Klason et al. [6] investigated the effect of secondary air on the combustion characteristics of wood pellets in a grate fired furnace. They compared flame temperatures, distributions of CO and NO_x concentrations experimentally and numerically. They reported that the biomass combustion can be controlled by the secondary and tertiary air injection. Lee et al. [7] researched to optimize the furnace design of a pellet stove with 30000 kcal/h capacity

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experimentally and numerically. As a result of their study, they said that efficient use of furnace volume is necessary for good gaseous mixing and combustion. Zhou et al. [8] aimed to optimize operating conditions and design parameters of straw combustion in a fixed bed. They observed that the simulation results (gas concentrations at the bed surface, ignition flame front, and bed temperature) were in good agreement with experimental results. Sui et al. [9] numerically investigated the biomass briquette combustion in the grate. They presented temperature, oxygen and carbon dioxide distribution as numerical results and evaluated them. Dong and Blasiak [10] aims to reduce emissions by more efficient combustion for 15 MW solid biomass fired boiler and 29 MW coal fired boiler, by distributing the secondary air into to the boiler. They used Arrhenius finite-rate reaction mechanism and the Magnussen and Hjertager eddy-dissipation model to calculate relationship between turbulence and chemistry. They took the biomass and coal gas reactions chemical data's directly adopted from the data generated by methane combustion reactions from the Fluent program and they stated that the numerical results were successful for prediction. Gomez et al. [11] experimentally and numerically compared the heat transfer, temperature and species concentration of a domestic pellet boiler. They stated that the numerical results were in acceptable level of accuracy in comparison to experiments. Also, they numerically investigated the effect of water temperature on a pellet boiler and they showed that low water temperature increased the heat transfer. Ahn and Kim [12] designed a pellet fuelled boiler and then performed experiments and numerical simulation with this boiler. They stated that the flame forms an arch from the second grate and this issue was predicted well by numerical simulations. Chen et al. [13] modified one of two coal-fired hot water boilers to wood pellet burning and investigated the total performance of the boilers (such as combustion characteristics and emissions) experimentally and numerically. They used the FLIC code and the Fluent program in numerical modeling. They stated that the flue gas temperatures were not in satisfactory agreement experimentally and numerically. Westerlund et al. [14] investigated the optimization of 20 kW pellet burner using CFD in their work. They did simulations only with the gas mixture approach. They pointed out that the original geometry of the burner gave inadequate performance. They noted that with the optimal design they obtained from the simulations, the output power increased and the unburned concentrations decreased but could be further reduced. They stated that the time of interaction between the combustion gases and the secondary air is probably short and that this increase in efficiency can have a positive effect.

In this study, the effect of the boiler geometry (two and four passes) on the combustion characteristics of a pellet fuelled boiler was analyzed numerically with Fluent program. Calculations were made for three dimensional conditions. As the turbulence model RNG k-ε model, as the combustion model Finite rate/Eddy dissipation model and as the radiation model P1 approach were used. Temperature contours, velocity vectors, exhaust gas temperatures and efficiencies were investigated for boilers with two and four passes and results were discussed.

II. MATERIALS AND METHODS

Pellet fuel combustion occurs in four stages, like other solid fuels (coal, briquete etc.) which are drying (evaporation of water), pyrolysis (separation of the volatile components), combustion of volatile components and combustion of fixed carbon [15].

Analytical, experimental and numerical methods can be applied for solving the combustion problems. These methods can be applied separately or together. Because of the developments in computer field, numerical methods have been used quite often in recent years. In this study Fluent program was used as CFD program and therefore some information was given about the details of the sub-models which were used in this program.

Fluent is a computational fluid dynamic program (CFD) which can model various processes like fluid motion, heat transfer, particle motion and combustion. It transforms the partial differential equations to algebraic equation form and solves these equations numerically. Various options are available for combustion modeling in Fluent program [16]. These are: species transport model, non-premixed model, premixed model, partially premixed model, composition PDF model.

Species transport model was used in this study for modeling the combustion, so brief description of this model is given. This model can be used to solve the problems as non-premixed combustion, premixed combustion and partial premixed combustion. In this approach, the conservation of the species mass fractions is defined by the user contains a solution of chemical reactions. The reaction rates and the relationship of turbulence-reaction are taken into account with Arrhenius equation and/or Magnussen-Hjertager equations by the following models: laminar finite rate, finite-rate/eddy dissipation, eddy dissipation and eddy dissipation concept models [16]. Finite rate/Eddy dissipation model computes both the Arrhenius and the Eddy dissipation rates and uses the smaller value as the reaction rate.

In this study, volatile components of pellet fuel were modeled at gas phase. The part of the fixed carbon was modeled by injecting carbon particles above the grate. Calculations were made at three dimensional conditions. For modeling the turbulence RNG k-ε model, for modeling the combustion Finite rate/Eddy dissipation model and for modeling the radiation P1 approach were used.

In reaction model, calculations were performed by entering the following equations to the program:

$$C_6H_6 + {}^{15}/_2\, O_2 \rightarrow 6CO_2 + 3H_2O \tag{1}$$

$$CH_4 + {}^{3}/_2\, O_2 \rightarrow CO + 2H_2O \tag{2}$$

$$H_2 + {}^{1}/_2\, O_2 \rightarrow H_2O \tag{3}$$

$$CO + {}^{1}/_2\, O_2 \rightarrow CO_2 \tag{4}$$

$$CO_2 \rightarrow CO + {}^{1}/_2\, O_2 \tag{5}$$

$$C < s > + O_2 \rightarrow CO_2 \tag{6}$$

The geometric dimension and the boundary conditions of the model boilers are given in Fig. 1 and the isometric views of the two boilers were given Fig. 2.

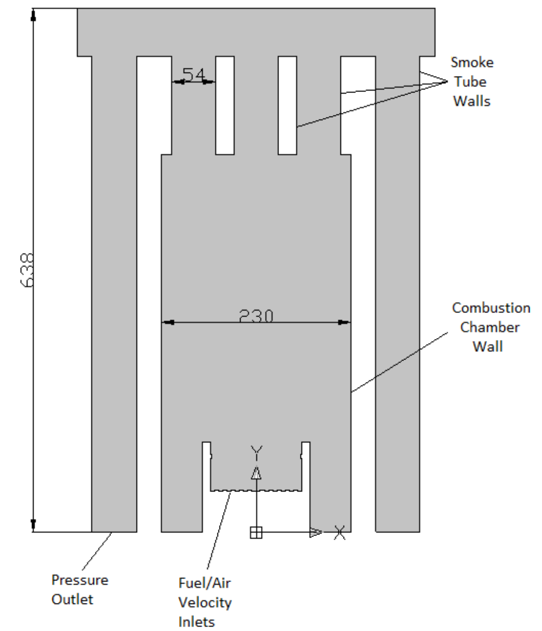

Fig. 1. Dimensions and boundary conditions of the pellet boilers

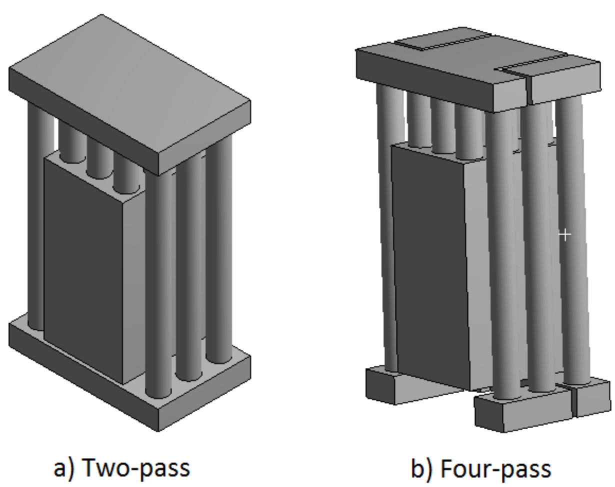

Fig. 2. Isometric views of the pellet boilers

The combustion gases pass through the furnace into 9 smoke tubes (first pass) and hit the upper smoke box and enter the 6 smoke tubes (second pass) which are on the side as shown in Fig. 3. In the case of four-pass, the flue gases pass through the furnace into 9 smoke tubes (first pass), hit the upper smoke box and directed downwards by entering into 2 smoke tubes (second pass), then enter into 2 smoke tubes (third pass) and directed upwards and finally pass through the two smoke tubes (fourth pass) at the rear as shown in Fig. 4. From there, the flue gases leave the boiler.

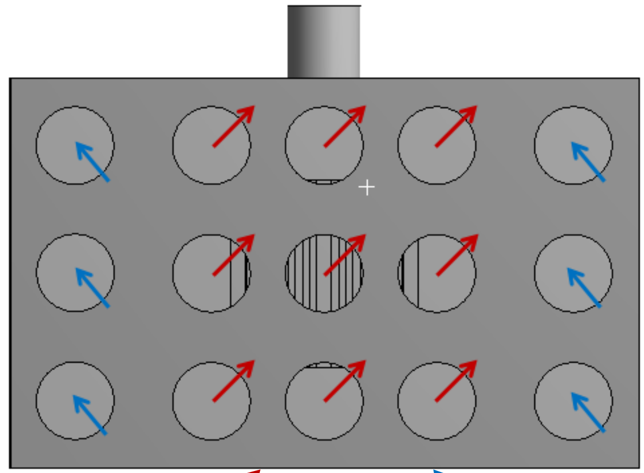

Fig. 3. Flue gas passes; : First pass outlet, : Second pass inlet

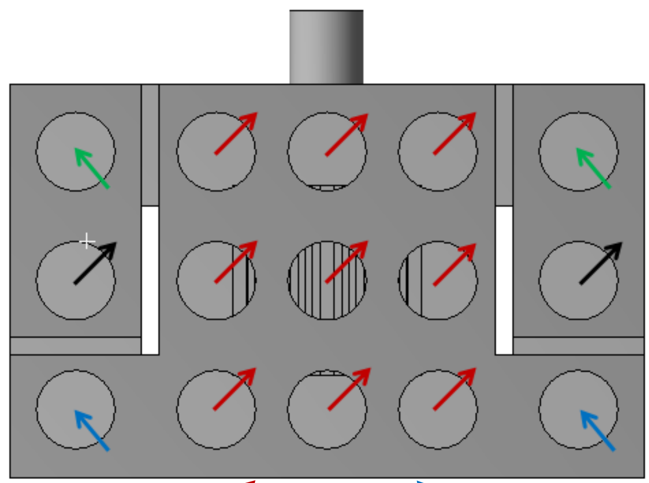

Fig. 4. Flue gas passes; : First pass outlet, : Second pass inlet, :Third pass outlet, :Fourth pass inlet.

The mesh structure of the two-pass boiler which was used in this study was shown in Fig. 5. This mesh has nearly 300000 cell with interval size of 1mm (medium mesh). Also coarser (interval size of 2.5 mm and finer (interval size of 0.5 mm) mesh structures were tried by pre-calculations. These calculations showed that the results of medium and fine mesh structures were close to each other, so in this study medium mesh was used. Also, the same calculations were realized for four-pass boiler and similar mesh structure was used in this boiler.

Calculations were performed with the boiler power of 30 kW for both boilers.

Fig. 5. Mesh structure of the pellet boiler with two passes

Properties of the pellet fuels were given at Table 1. The amount of moisture content in the fuel is considered by adding it to the gas phase. It is assumed that the volatile components consist of CO, CO_2, H_2, H_2O, light hydrocarbons (CH_4) and tar (C_6H_6) [11].

Table 1. Properties of the pellet fuel [11]

Proximate analyses	
Moisture [wt %]	8.50
Ash [wt %]	0.62
Fixed carbon [wt.%]	16.20
Volatile matter [wt.%]	74.68
Lower heating value [kJ/kg]	18330

All the calculations were made with %100 excess air. All surfaces in contact with water considered as wall with a temperature of 353 K. Outlet region was introduced as pressure outlet where atmospheric pressure prevails, air inlet and fuel inlet were introduced as velocity inlet. Iterations were continued up to the value of 10^{-6} for continuity and energy convergence criteria.

III. RESULTS AND DISCUSSIONS

The temperature contours of pellet fuel combustion for two and four pass boilers are shown in Fig. 6. Figure shows that, flame temperatures reached to their maximum values in areas near to the grate in both boilers, and temperatures decreased toward the exit because the hot gases areas surrounded by water. In the combustion chamber, regions close to the water jackets, temperatures were about 533-843 K in the case of two pass, 533 - 765 K in the case of four pass. In both cases, the cross-sectional images taken from the boiler center were found to have higher temperatures than the other zones. It is also seen that the temperatures in the front section of the boiler are higher than the temperatures in the rear section. While the maximum temperature in the case of a two-pass boiler is around 1873 K, in the case of a four-pass boiler, this value is around 1713 K.

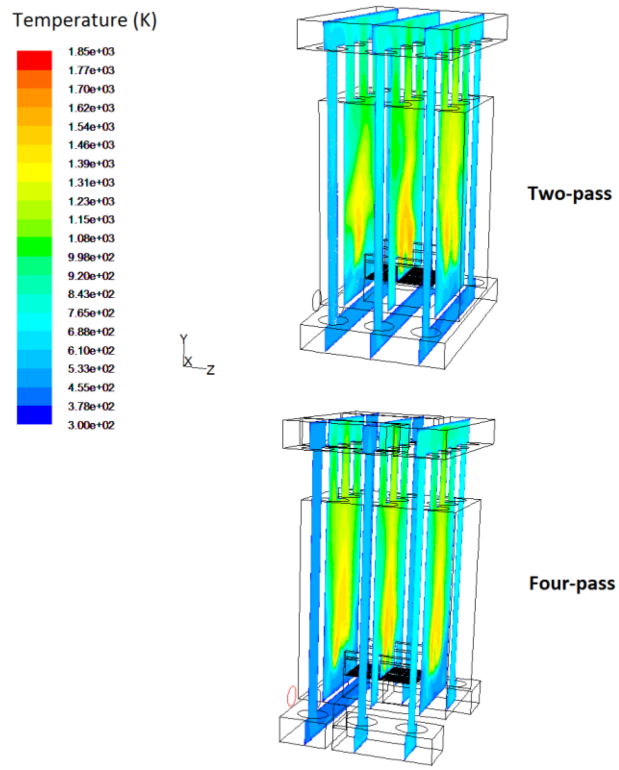

Fig. 6. Temperature contours of the boilers

Fig. 7 illustrates the velocity vectors of the boilers. As shown in the figure, the flue gases pass through the furnace into 9 smoke tubes (first pass) and hit the upper smoke box and enter the 6 smoke tubes (second pass) which are on the side. Then, these gases exited from the chimney.

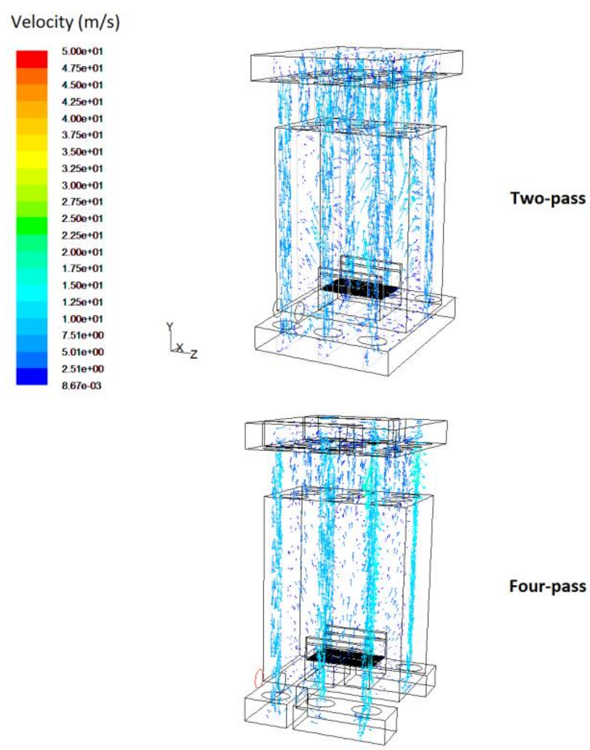

Fig. 7. Velocity vectors of the boilers

In the case of four-pass, the flue gases pass through the furnace into 9 smoke tubes (first pass), hit the upper smoke box and directed downwards by entering into 2 smoke tubes as seen from the front section. Then, as seen in the middle section, the gases enter into 2 smoke tubes and directed upwards and finally pass through the two smoke tubes at the rear and exited from the chimney.

The efficiency of a boiler can be calculated with Eq.(7) as follows [17], if losses are neglected except sensible heat of flue gases:

$$\eta = 1 - (1 + \lambda A_{sto})(T_{exh} - T_0)c_{p,exh} / H_U \quad (7)$$

In this equation λ is excess air coefficient, A_{sto} is stoichiometric air fuel ratio, $c_{p,exh}$ is specific heat of exhaust gases, T_{exh} is exhaust gas temperature, T_{amb} is ambient air temperature and H_U is lower heating value of the fuel.

According to this equation the exhaust gas temperatures can be used for comparison the boiler efficiencies. The exhaust gas temperatures for two-pass boiler and four-pass boiler are, 458 K and 410 K, respectively. Accordingly, as the number of passes increases, the exhaust gases temperature decreases and the boiler efficiency increases. While the two-pass boiler efficiency is 86.5%, this value is about 90.4 % in the four-pass boiler.

The temperature and efficiency values of this study are compatible with the literature. Gomez et al. [10] numerically investigated the domestic pellet boiler with 18 kW power, and they reported that the maximum temperatures were about 1873 K and occurred close to the grate, exhaust gas temperature was 461 K and efficiency was 77.2%. Lee et al. [6] investigated the domestic pellet boiler with 35 kW capacity and stated that the maximum flame temperatures were about 1530 K-1760 K. They also said that in the existing pellet boiler the exhaust gas temperature was about 443 K. Collazo et al. [4] experimentally and numerically analyzed the domestic pellet boiler with 18 kW capacity. They obtained from the numerical simulations that at λ=2.1, the exhaust temperature was nearly 423 K, at λ=2.25 the exhaust temperature was about 428 K, at λ=2.6 the exhaust temperature was about 443 K and at λ=3 the exhaust temperature was about 448 K. Maximum gas temperatures were about 1773 K and occurred near to the grate.

IV. Conclusions

The main aim of this study is to compare the effects of pellet boiler geometry on combustion characteristics. In this context, temperature contours, velocity vectors, exhaust gas temperatures and efficiencies were determined for two-pass and four-pass boilers and results were evaluated. Examining the results of the two and four pass boilers showed that the flue gas temperature of the four-pass boiler is about 50 K lower than that of the two pass boiler and the thermal efficiency is about 4% better. Different methods can be developed to improve the efficiency like inserting turbulators to the smoke tubes in the boiler for prevent the high exhaust gas temperatures. Also, the combustion model can be developed by applying more detailed calculation for the combustion process (drying, gasification, fixed carbon combustion) of solid fuels.

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