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Numerical Analyses of the Effects of Fuel Load Variation on Combustion Performance of a Pellet Fuelled Boiler

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Abstract: Domestic and industrial energy requirements since the beginning of industrial revolution have been largely met by fossil fuels. This leads to a continuous increase in the Earth's atmosphere of carbon dioxide and other harmful components. Also, fossil energy resources decreasing day by day and scientists have turned to new research. In this context alternative energy sources have an important role to reduce dependence on fossil fuels. One of the alternative energy sources is biomass and pellet fuel is one of them. In this study, combustion characteristics of pellet fuel in a model smoke tube boiler at different loading conditions were investigated numerically. As a Computational Fluid Dynamic (CFD) program FLUENT package program was used. Calculations were performed at two dimensional conditions. According to various loading conditions, temperature and stream function contours, velocity vectors, exhaust gas temperatures and efficiencies were investigated and results were discussed. With decreasing thermal load, the exhaust gas temperatures decreased and boiler efficiencies increased. By reducing thermal power from the maximum value of 75 kW to the minimum value of 30 kW, the exhaust gas temperature decreased from 585 K to 429 K, whereas the thermal efficiency increased from 76% to 89%

Keywords: Biofuels, Numerical modeling, Pellet, Pellet boilers

1. Introduction

Today, 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 with 30% (Sungur et al., 2017). Studies on biomass which is one of the renewable energy sources has gained importance recently. Positive features of biomass fuels in terms of economic and environmental are among the reasons to prefer this renewable source. Some countries see bioenergy as the main energy source of the future and benefit from this energy source with a significant amount. 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 can be made from sawdust, wood chips, bark, waste, agricultural products, stems of crops, hazelnut, almond and walnut shells etc. These materials, compressed under

high pressure after grinding and typically 6-8 mm in diameter, 10-11 mm in length, with a cylindrical structure and it's called with the name of pellet. Pellet fuel is a sustainable resource and has many advantages: reduces fossil fuel imports, contributes to the economy, leaves less waste after usage, and leads to exhaust emissions within acceptable limits.

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Considering the scope of this study a literature search was carried out on the numerical modeling of the combustion of solid fuel boilers. (Begum et al., 2014) investigated the fluidized bed gasification of solid waste experimentally and numerically. They did their experiments on a pilot scale gasifier and they used Advanced System for Process Engineering (Aspen) Plus software for numerical calculations. They stated that experimental and numerical methods were in good agreement and they 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., 2009) carried out numerical analyses with Fluent 6.3 program on 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, CO2, H2O, H2, light hydrocarbons (CH4) and heavy hydrocarbons (C6H6). As a result they compared the gas temperatures and concentrations with numerical and experimental methods and they stated that the results were in good agreement. (Chaney et al., 2012) investigated the combustion performance and NOx emissions optimization of 50 kW pellet boiler. They said that there are many parameters which can improve the combustion performance and NOx 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., 2012) 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 and Bai, 2007) 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 concentrations experimentally and numerically. They stated that the biomass combustion can be powerfully controlled by the secondary and tertiary air injection. (Lee et al., 2011) researched to optimize the furnace design of a pellet stove with 30000 kcal/h capacity experimentally and numerically. As a result of their study, they said that for good gaseous mixing and combustion efficient use of furnace volume is necessary. (Zhou et al., 2005) 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., 2013) 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, 2001) numerically analyzed the systems distributed the secondary air into to the boiler, which aims to reduce emissions by more efficient combustion for 15 MW solid biomass-fired and 29 MW coal-fired boilers, respectively. They used Arrhenius finite-rate reaction mechanism and the Magnussen and Hjertager eddy-dissipation model to calculate the 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. (Gómez et al., 2012) compared the heat transfer, temperature and species concentration of a domestic pellet boiler. As a result, 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, 2014) designed a pellet fuelled boiler and then they carried out 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.

From the literature, it can be seen that the studies mainly focused on investigating the amount, number and positions of the secondary air, air inlet distributions, positions of the water tubes and comparing these effects on the performance and emissions of a boiler. In this study, combustion characteristics of a model pellet boiler for various loading conditions were analyzed numerically with Fluent program. Calculations were made for two-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 was used. Temperature and stream function contours, velocity vectors, exhaust gas temperatures and efficiencies were investigated for various loading conditions and results were discussed.

2. Material and Method

Pellet fuel combustion occurs in four stages, like other solid fuels which are drying (evaporation of water), pyrolysis (separation of the volatile components), and combustion of volatile components and combustion of fixed carbon as shown in Figure 1 (Pelletsatlas, 2009).

In the solution of combustion problems analytical, experimental and numerical methods can be applied. These methods can be applied separately, or they can be used together. Due to developments of powerful computers, 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 submodels which were used in this program.

Fluent is a computational fluid dynamics 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 (Fluent, 2006). These are species transport model, non-premixed model, premixed model, partially premixed model, composition PDF model.

For the combustion modeling, species transport model was used in this study so brief description of this model are given below:

Species Transport Model: 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 (Fluent, 2006). Finite rate/Eddy dissipation model computes both the Arrhenius and the Eddy dissipation rates and uses the smaller value as the reaction rate.

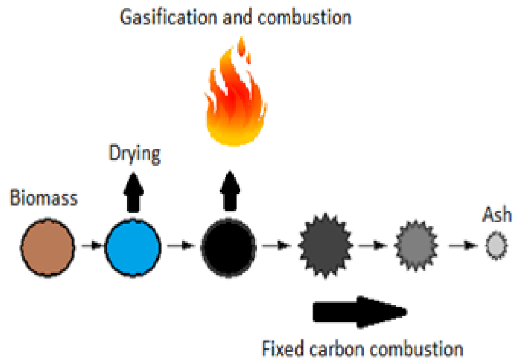

Figure 1. Pellet fuel combustion steps (Pelletsatlas, 2009)

In this study, volatile components of pellet fuel were modeled at a gas phase in a model boiler. The part of the fixed carbon was modeled by injecting carbon particles above the grate. Calculations were made at two-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 into the program:

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

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

$$H_2 + {}^{1}/_2\, O_2 \rightarrow H_2O \qquad (3)$$

$$CO + {}^{1}/_2\, O_2 \rightarrow CO_2 \qquad (4)$$

$$CO_2 \rightarrow CO + {}^{1}/_2\, O_2 \qquad (5)$$

$$C < s > + O_2 \rightarrow CO_2 \qquad (6)$$

The geometric dimension of the model boiler is given in Figure 2. Because of the boiler considered as symmetric, calculations were carried out for only one half of the boiler.

The mesh structure of the boiler which was used in this study was shown in Figure 3. This mesh has a 102704 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 (Table 1), so in this study, medium mesh was used.

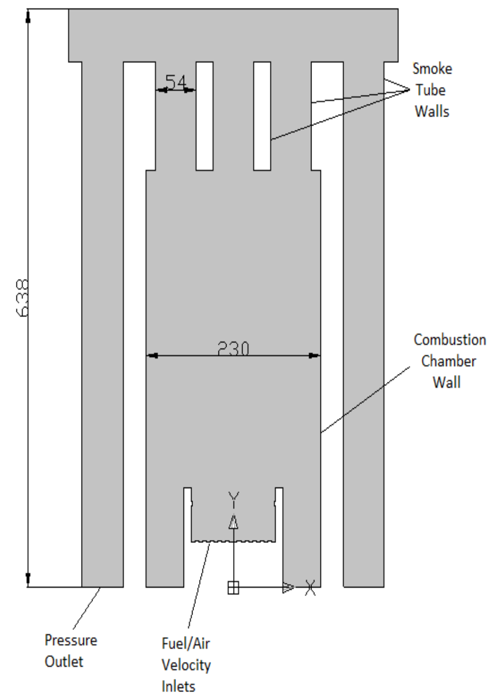

Figure 2. Dimensions of the pellet boiler

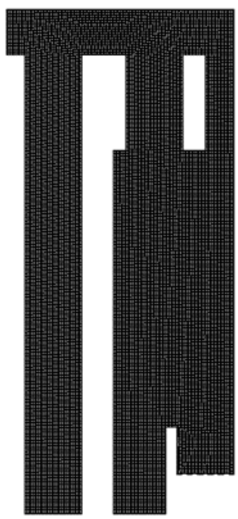

Figure 3. Mesh structure of the pellet boiler

Table 1. Effect of the mesh size for 30 kW boiler power

Mesh Size	Max Temp (K)	Exhaust Temp. (K)
Coarse	1663,7	454,48
Medium	1832,2	428,5
Fine	1853,6	422,4

Calculations were performed with the boiler power of 30 kW which is the minimum loading, 45 kW, 60 kW, and 75 kW which is defined by full loading conditions. Properties of the pellet fuels were given in Table 2. 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, NH_3, light hydrocarbons (CH_4) and tar (C_6H_6) (Gómez et al., 2012).

Table 2. Properties of the pellet fuel (Gómez et al., 2012)

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 for the constant value of excess air coefficient λ=2. All surfaces in contact with water considered as the wall temperature of 353 K. Outlet region introduced as pressure outlet where atmospheric pressure prevails, air inlet and fuel inlet are introduced as velocity inlet. Iterations were continued up to the value of 10-6 for continuity and energy convergence criteria.

3. Results and Discussions

The temperature contours of pellet fuel combustion are shown in Figure 4. As can be seen from the figure, in all cases flame temperatures reached to their maximum values in areas near to the grate, and temperatures decreased toward the exit because of the hot gases areas surrounded by water. In the case of full loading conditions (75 kW), mean temperatures in the boiler are higher than the other cases because of the effect of increasing power. In the case of minimum loading conditions (30 kW) the maximum flame temperature (1897 K) occurred near to the grate region and was higher than the other cases due to the effect of low gas velocities. The maximum flame temperature values were close to each other in other loading conditions with the temperature of about 1845 K. In the combustion chamber, regions close to the water jackets, temperatures were about 561-626 K in the case of 30 kW, 618 - 682 K in the case of 45 kW, 679 - 743 K in the case of 60 kW and 743 -807 K in the case of 75 kW. In the inlet section of the central smoke tube of the first pass (located above the flame) gas temperatures were about 1020 - 1080 K at 30 kW, 1130 K-1190 K at 45 kW, 1190 - 1250 K at 60 kW and 1250 - 1310 K at 75 kW. The gas temperatures in the inlet section of side tubes of the first pass were about 822 - 887 K, 873 – 936 K, 996 - 1060 K and 1060 - 1120 K in the case of 30 kW, 45 kW, 60 kW and 75 kW, respectively. From the first pass, the gas flow turned to the second pass and cooled further towards the exit.

Figure 5 shows the stream function contours. The flow of hot gases which occurred as a result of fuel combustion created a vortex in the combustion chamber and near to the water channel, then turned towards the smoke tubes and exited the boiler properly. Gas velocities decreased with the effect of decreasing loading conditions from full load to low load and consequently the stream function values decreased too. Also velocity vectors were given in Figure 6. As can be seen from this figure the gas velocities increased with increasing boiler heat power.

The efficiency of a boiler can be calculated with Eq.(7) as follows (Sungur et al., 2016), if losses are neglected except sensible heat of flue gases:

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

In this equation λ is excess air coefficient, Asto is stoichiometric air fuel ratio, cp,exh is specific heat of exhaust gases, Texh is exhaust gas temperature, Tamb is ambient air temperature and HU is lower heating value of the fuel.

According to this equation the exhaust gas temperatures can be used for comparison the boiler efficiency by changing loading conditions. In Figure 7, exhaust gas temperatures and efficiencies are given for various loading conditions. The maximum exhaust gas temperature occurs in the case of full loading conditions with the temperature of 585 K, and the minimum exhaust gas temperature occurs in the case of minimum loading conditions with the temperature of 429 K. Accordingly, with the increasing heating power the exhaust gas temperatures increased and boiler efficiencies decreased. The maximum boiler efficiency was 89% at 30 kW heat power and the minimum efficiency value is 76% at 75 kW heat power.

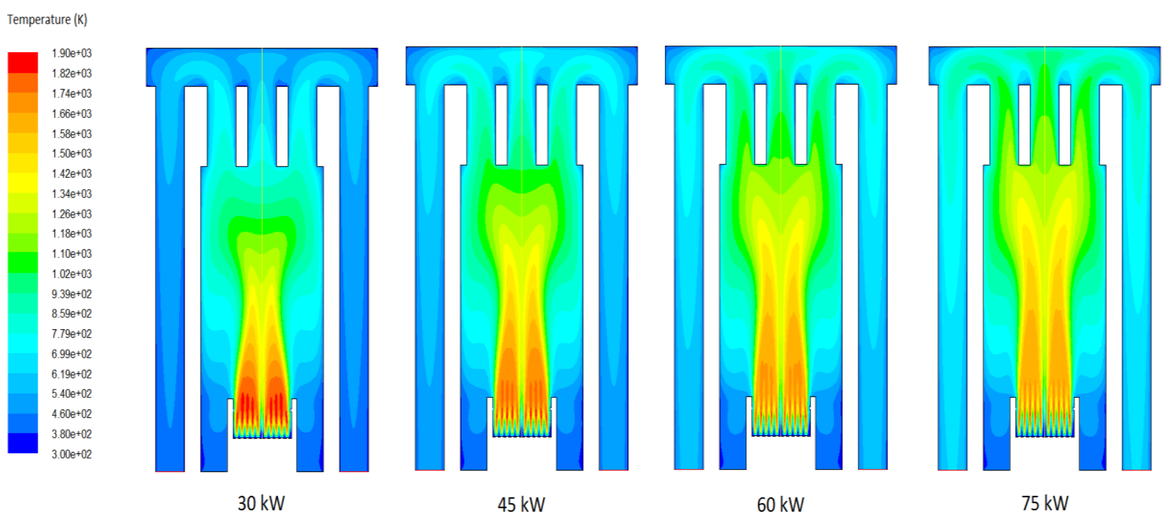

Figure 4. Temperature contours for various loading conditions

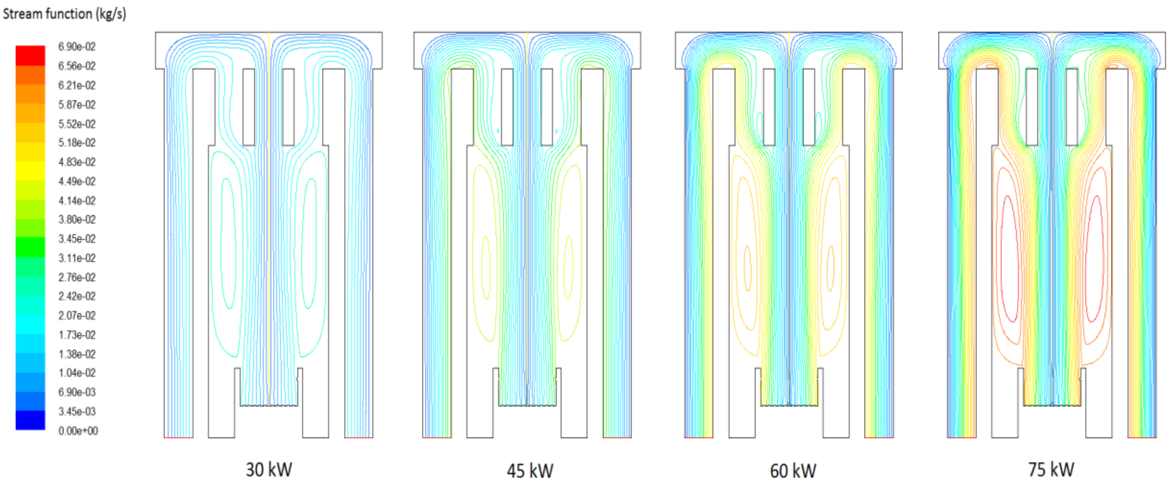

Figure 5. Stream function contours for various loading conditions

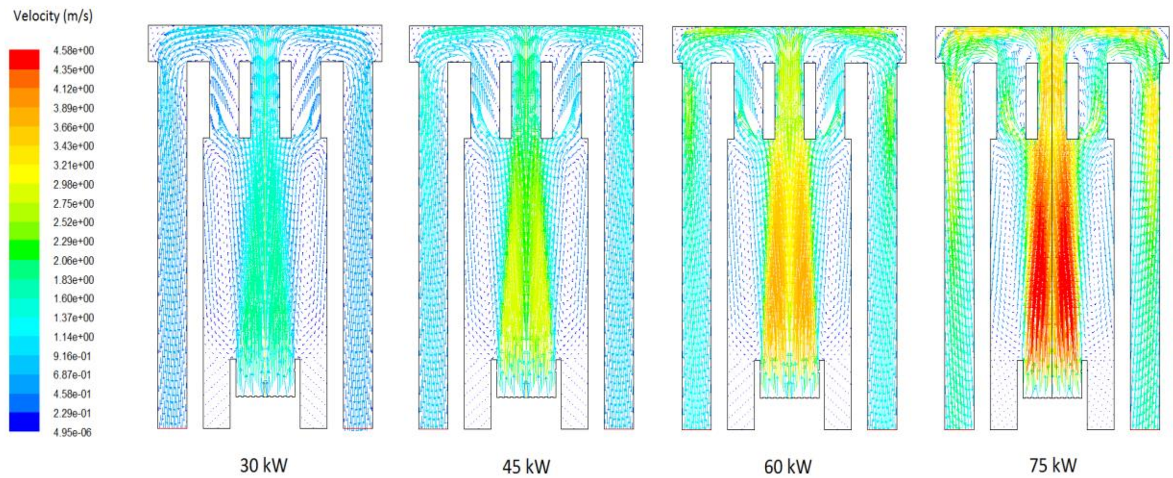

Figure 6. Velocity vectors for various loading conditions

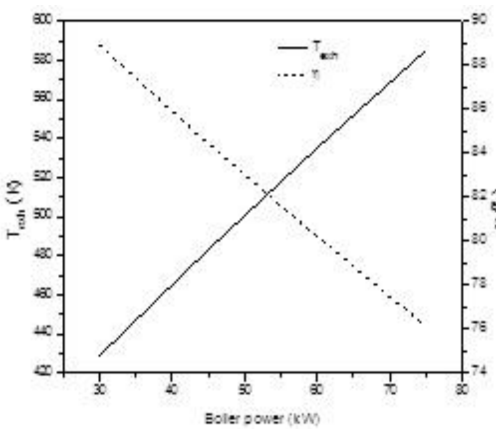

Figure 7. Exhaust gas temperatures and efficiencies for various loading conditions

These values are compatible with the literature. In the study of (Gómez et al., 2012), they numerically investigated the 18 kW domestic pellet boiler performance 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., 2011) investigated the domestic pellet boiler with 35 kW capacity and aimed to design an optimal furnace for the boiler. They experimentally and numerically investigated different furnace geometries 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., 2012) 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. With increasing, air/fuel excess ratio hot gas regions increased through the combustion chamber.

4. Conclusions

In this study, combustion in a model pellet boiler is analyzed numerically for various loading conditions. Temperature and stream function contours, velocity vectors, exhaust gas temperatures and efficiencies were determined for various loading conditions and results were evaluated. As a result of calculations, the exhaust gas temperatures increased and boiler efficiencies decreased with the increasing heating power. In the case of full loading conditions, the maximum exhaust gas temperature occurred with a value of 585 K, whereas the minimum exhaust gas temperature occurred with a value of 429 K in the case of minimum loading conditions. The efficiency of the boiler increased as the temperature of the exhaust gas decreased. The maximum boiler efficiency was obtained at 30 kW heat power with the value of 89% and the minimum efficiency value was obtained at 75 kW heat power with the value of 76%.

To improve the efficiency different methods can be developed according to the boiler loading conditions. For example, turbulators can be inserted to the smoke tubes in the boiler for prevent the high exhaust gas temperatures in the case of full loading conditions. In future studies, the combustion model can be developed by applying more detailed calculation for the combustion process (drying, gasification, fixed carbon combustion) of solid fuels. In this way, the effect of various loading variations on the harmful exhaust emissions such as NOx can be also calculated.

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