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Research Article

Experimental Investigation of the Effect of Feeding System on the Performance at Pellet-Fuelled Boilers

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Abstract
Depending on the growing industry and the population, energy needs are increasing day by day. This issue makes it necessary the use of renewable energy sources as much as possible. There is a growing interest in pellet fuel and pellet-fired combustion systems, which are one of the renewable energy sources. In this work, performance analyzes of pellet-fueled boilers with two different feeding systems (horizontal-fed and top-fed) and two different flue gas outlet positions were carried out and results were discussed. Emissions of O_2, CO and NO_x and flue gas temperature were measured at a certain point of the chimney. Boiler thermal efficiencies were calculated and compared with each other. Direct and indirect methods were used to calculate thermal efficiency of boilers. Results showed that the flue gas temperatures were about 110 °C in the top-fed boiler and 138°C in the horizontal-fed boiler. The thermal efficiency of top-fed boiler was higher than horizontal-fed boiler. In the top-fed boiler, CO and NO_x emissions were lower than the horizontal-fed boiler. Generally, the top-fed boiler showed better performance in terms of thermal efficiency and lower emission characteristics than horizontal-fed boiler.

Keywords: Biofuels, pellet, pellet boilers, boiler design, pellet feeding systems

Pelet Yakıtlı Kazanlarda Besleme Sisteminin Performansa Etkisinin Deneysel İncelenmesi

Öz
Büyüyen sanayi ve artan nüfusa bağlı olarak enerji ihtiyacı da her geçen gün artmaktadır. Bu durum mümkün olduğu kadar yenilenebilir enerji kaynaklarının kullanımını zorunlu kılmaktadır. Bu anlamda yenilenebilir enerji kaynaklarından pelet yakıtı ve pelet yakıtlı yakma sistemlerine ilgi giderek artmaktadır. Bu çalışmada, iki farklı besleme sistemine (yatay beslemeli ve üstten beslemeli) ve iki farklı baca gazı çıkış konumuna sahip pelet yakıtlı kazanların performans analizleri yapılmış ve sonuçlar tartışılmıştır. Bacanın belirli bir noktasından O_2, CO ve NO_x emisyonları ve baca gazı sıcaklıkları ölçülmüştür. Kazan ısıl verimleri hesaplanmış ve birbirleriyle karşılaştırılmıştır. Kazanların ısıl verimlerinin hesaplanmasında direkt ve endirekt yöntemler kullanılmıştır. Sonuçlar, baca gazı sıcaklıklarının üstten beslemeli kazanda yaklaşık 110 °C ve yatay beslemeli kazanda 138 °C olduğunu göstermiştir. Üstten beslemeli kazanın ısıl verimi yatay beslemeli kazandan daha yüksek çıkmıştır. Üstten beslemeli kazanda, CO ve NO_x emisyonları yatay beslemeli kazandan daha düşük çıkmıştır. Genel olarak, üstten beslemeli kazan, yatay beslemeli kazandan termal verim açısından daha iyi performans ve daha düşük emisyon özellikleri göstermiştir.

Anahtar Kelimeler: Biyoyakıtlar, pelet, pelet kazanları, kazan dizaynı, pelet besleme sistemleri

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1. Introduction

Rapid population growth, industrialization, and technological progress lead to an increase in energy demand. Energy is the most increasing and necessary input in today's production process. Non-renewable fossil energy sources can be consumed in the near future and generate environmentally harmful emissions, so using renewable sources become more attractive. Approximately 1/3 of the world's population uses solid fuel (coal, biomass etc.) for heating and cooking purposes, and this amount is constantly increasing, given that the population is constantly growing [1]. Air pollution caused by domestic use created serious health problems that caused about 2.8 million premature deaths in 2015 [2-4]. Also, solid fuel (especially coal) combustion has adverse effects on environment [5,6]. Renewable energy is naturally replenished on a human timescale and collected from natural renewable resources, such as hydraulic, solar, wind, geothermal, hydrogen, and biomass. Pellet fuel has a significant potential in renewable energy sources and have positive effects on socio-economic development. Pellets are produced by compressing the organic products and wastes such as walnut shells, nuts, wood chips, sawdust, agricultural products, etc.

Boilers are defined as an arrangement of vessels and tubes with a furnace, where water or other fluid is heated by combustion of fuel and generally used for heating or power applications. Boilers can be used generally in residential areas for heating purposes or in many industries which require energy.

The boiler efficiency depends to the combustion quality and the heat transfer amount to the fluid. Flue gas emissions depend on the amount of pollutants in the fuel, the design of the boiler, burner, grate, feeding type and the operating conditions. To reach a complete combustion with low emissions and low slag in the pellet combustion, the amount of combustion air and the mode of the delivery method are very important. To provide the ideal combustion, the mixture of fuel and combustion air must be provided under optimum conditions.

In regard to loading system, solid fuel boilers are categorized as manually or automatically. In manual systems, the pellet is supplied to the combustion chamber and burned with air which is naturally or forced draft. In automatic systems, the pellet is fed to the combustion chamber from top, horizontal or bottom via screw conveyor which transport the pellet into the grate. The grate has gaps and the combustion air is supplied from these gaps to the pellet.

The objectives of the studies in the available literature are mainly focused on reducing the high air excess, flue gas temperatures as much as possible, harmful flue gas emissions, efficiency enhancement and providing optimal fuel/air ratio using the lambda sensor. For example, Carroll et al. [7] analysed the effect of excess air ratio on the temperature, NO_x and PM emissions at modified biomass boiler with 35 kW thermal power. They found that the change in primary excess ratio reduced the PM and NO_x emissions 26% and 15%, respectively. Li et al. [8] experimentally searched the effect of secondary air (SA) ratio to primary air (PA) ratio on NO_x emissions at 210 kW fixed grate furnace. They found that the lowest NO_x emissions were obtained at the value of 0.4 for SA/PA, 0.71 for PA to total air ratio and 2.04 for air excess.

Lamberg et al. [9] surveyed the effect of air staging on pollutant gas emission at 25 kW pellet boiler. They stated that the significant decrease in CO emissions can be achieved by decreasing the PA amount at constant total air ratio. An experimental investigation of the gaseous emissions of NO_x, CO and PM at 50 kW biomass boiler with three types of biomass pellets carried out by Qiu [10]. He concluded that the supply of PA has an important role in combustion and more biomass fuel was burnt with increasing PA flow rate. Zadravec et al. [11] aimed to obtain correlations between the emissions and combustion temperatures at different primary and secondary air ratios and excess air conditions in small-scale wood pellet boiler. They stated that air staging has great importance to decreasing harmful emissions and sensible heat losses. Khodaei et al. [12] investigated the effect of air staging on gaseous and PM emissions at 15 kW wood pellet combustor. They found that distributing a uniform SA at higher position from the bed caused 50% reduction of CO and less particle emissions. Sungur and Topaloglu [13] researched the performance of a pellet boiler with different smoke tube configurations. They found that addition of smoke tubes to first pass decreased the flue gas temperatures and increased the thermal efficiency.

Literature survey showed that there is no detailed study of the effect of pellet fuel feeding systems and the flue gas outlet positions on the performance of a pellet fueled boilers. In this study, performance analyzes of pellet-fueled boilers with two different feeding systems (horizontal-fed and top-fed) and two different flue gas outlet positions were carried out and effect of these systems on flue gas temperature, thermal efficiency, and exhaust gas emissions were evaluated.

2. Materials and Methods

This study aimed to investigate the effect of fuel feeding types and the flue gas outlet positions on the performance characteristics of the automatic load pellet boiler. Experiments were carried out for two different feeding types which were horizontal-fed and top-fed with two different boilers. These boilers have approximately equal heat transfer surfaces.

The horizontal-fed boiler and its burner are shown in Figure 1. Pellet fuel was taken to the pellet burner through the stoker screw in the specified time. The ignition of pellets was provided by an electric resistance and after this the flame occurred in combustion chamber. The flame exited the burner tube first in the horizontal direction and then turned upwards. The combustion gases hit the refractory material on the top of the boiler, returned back and then directed to smoke tubes which have turbulators to increase the heat transfer. The flue gas passed through the sixteen smoke pipes surrounded by water and transferred the heat to the water and exited via an exhaust pipe from the top the boiler.

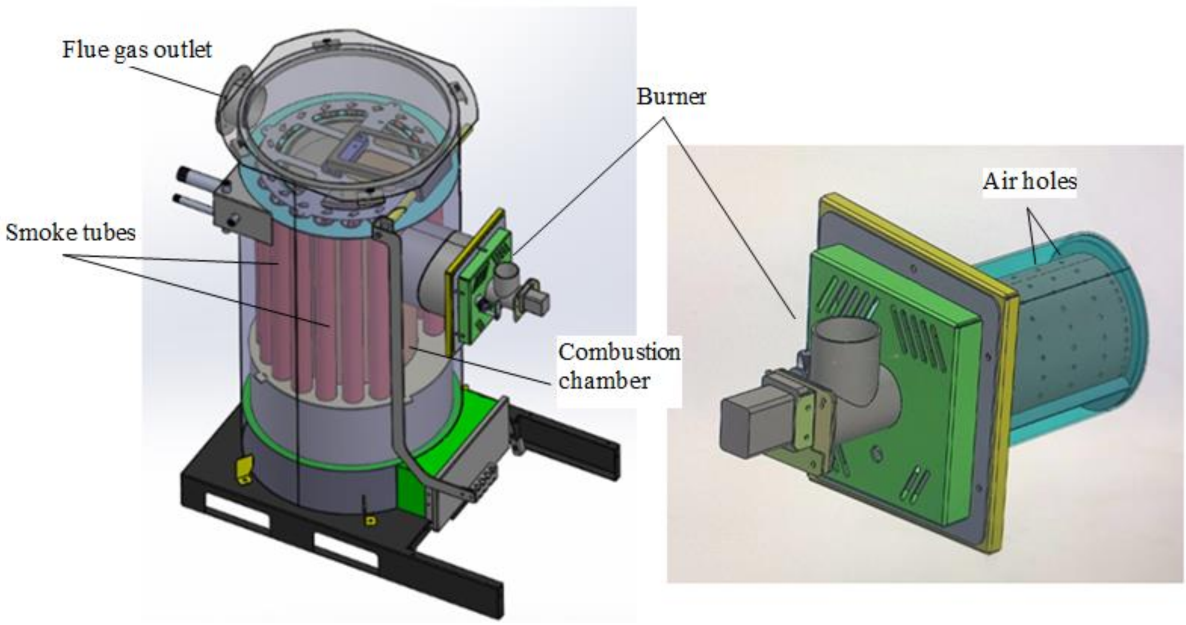

Figure 1. Isometric view (left) and burner (right) of the horizontal-fed boiler

The top-fed boiler and its grate are shown in Figure 2. Pellets dropped from top into the grate and then flame occurred in the combustion chamber. Combustion gases move upwards first and then directed to the twelve smoke tubes with turbulators and transferred its heat to the surrounded water. Finally, the flue gas exited via an exhaust pipe from the bottom of the boiler.

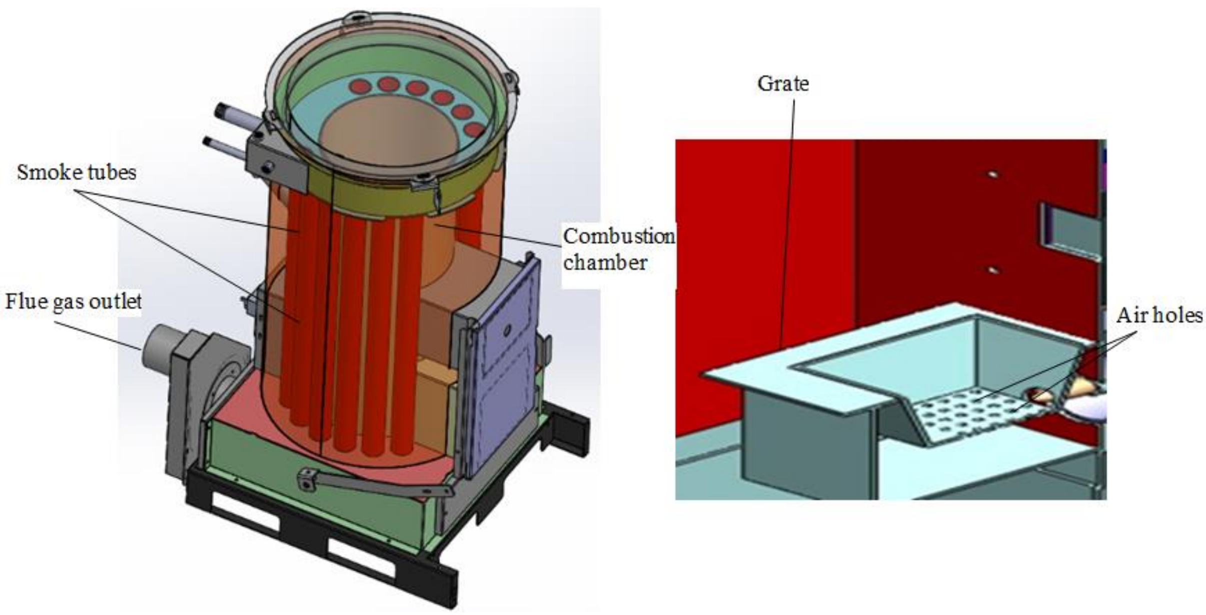

Figure 2. Isometric view (left) and grate (right) of the top-fed boiler

The characteristics of the two boilers with different feeding systems are summarized in Table 1. As shown in table, the boilers have different smoke tube lengths and numbers. The diameters of the smoke tubes used in both boilers are the same and in this sense, the main parameters affecting the heat transfer area are the length and number of the smoke tubes. In the light of this information, it should be known that the horizontal-fed boiler and the top-fed boiler have approximately the equal heat transfer surfaces (0.35% difference).

Table 1. Properties of the horizontal-fed and top-fed boilers

Properties	Horizontal-fed boiler	Top-fed boiler
Feeding type	Horizontal	Top
Combustion system type	Burner	Grate
Smoke Tube Length (mm)	715	950
Smoke Tube Number	16	12
Flue gas outlet position	Top	Bottom
Fuel Power (kW)	60	60
Fuel Tank Capacity (kg)	300	300
Fuel Consumption (kg/h)	12	12

The pellets were purchased from the market consisting of beech (70%) and pine (30%) components in certain rates and sold commercially in Turkey. The average length and diameters are 10-30 mm and 6 mm, respectively. To determine the heating value bomb calorimeter was used and the lower heating value of pellet is obtained as 18 MJ/kg.

The experimental setup is schematically illustrated in Figure 3. The system was stated on a digital weight scale and the fuel consumption was measured by this digital weight scale. A calorimeter was used to measure the heat transfer to the water. To measure the flue gas emissions Ecom-J2KN emission gas analyzer was used. Measurements were taken every 60 seconds from the gas analyzer and calorimeter device. Each experiment lasted approximately 1 hour and was repeated 3 times, and these values were averaged.

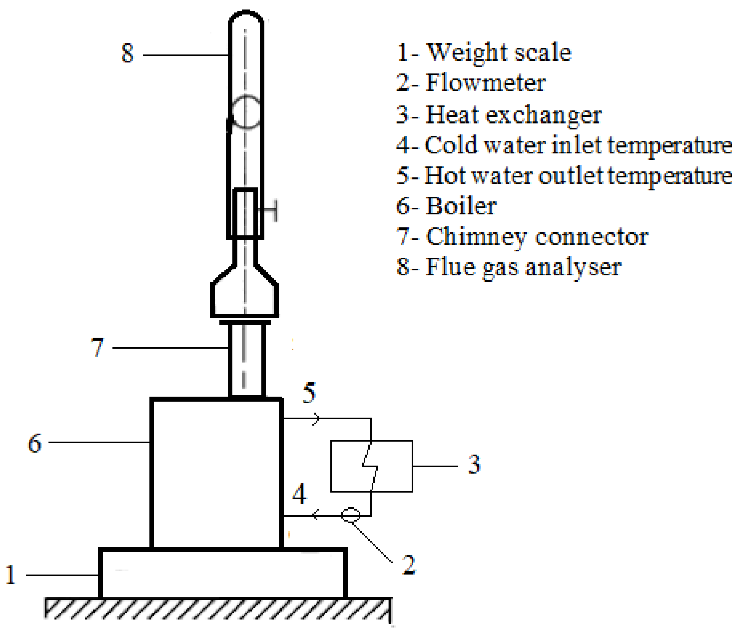

Figure 3. Scheme of the experimental setup

In both experiments, approximately 100% excess air was used. Results were recorded during for a period of about 55 min, when the system became nearly steady.

Two methods, direct and indirect, have been used to calculate thermal power and efficiency of the boilers. In direct method, the heat transfer to the water was directly measured and then the boiler thermal power was calculated. To calculate boiler thermal efficiency the total heat rate of the boiler divided to the fuel heat rate. In indirect method, flue gas sensible heat loss, unburned carbon monoxide loss, hydrocarbon loss, surface heat losses (radiation and convection) determined and thermal efficiency is calculated as follows:

$$\eta_{indirect} = \frac{\dot{Q}_{fuel} - \dot{Q}_{fg} - \dot{Q}_{CO} - \dot{Q}_{UC} - \dot{Q}_{s}}{\dot{Q}_{fuel}} = 1 - q_{fg} - q_{CO} - q_{UC} - q_{s} \quad (1)$$

where, $\dot{Q}_{fg}$, $\dot{Q}_{CO}$, $\dot{Q}_{UC}$ and $\dot{Q}_{s}$ are heat rates of flue gas, unburned CO, unburned carbon and surface heat losses, respectively. q_{fg} is the sensible heat loss of flue gas, q_{CO} is the loss from unburned CO in the flue gas, q_{UC} is the loss from unburned carbon in the residual and q_{s} is the surface loss due to radiation and convection.

q_{fg} can be calculated as follows:

$$q_{fg} = (1 + \lambda A_{sto})(T_{exh} - T_{amb})c_{p,exh} / LHV_{fuel} \quad (2)$$

In this equation λ represents the excess air coefficient, A_{sto} represents stoichiometric air/fuel ratio, $c_{p,exh}$ symbolizes specific heat of exhaust gases, T_{exh} is exhaust gas temperature and T_{amb} is ambient air temperature and LHV is lower heating value. The loss of CO and other details of the formulas can be found in [13,14]

q_{UC} which is the energy loss of unburned carbon is neglected. Surface losses (q_{s}) are not considered because of the fiberglass insulation and their measurement difficulties.

Uncertainties, in the gas analyzer (based on the manufacturer's data) and the technical characteristics of the gas analyzer were given in Table 2.

Table 2. Technical characteristics of the Ecom-J2KN gas analyzer

	Range	Accuracy	Resolution	Sensor type
O_2	0-20% vol	± 0.2% vol	0.1% Vol.	Electrochemical
CO	0-10000 ppm	± 2% measured	1.0 ppm	Electrochemical
NO	0-5000 ppm	± 5% measured	1.0 ppm	Electrochemical
NO_2	0-1000 ppm	± 5% measured	1.0 ppm	Electrochemical
Gas temp	0-1000 °C	± 0.5%	-	-

3. Results and Discussion

In combustion systems, there is a relationship between the efficiency and the flue gas temperature as mentioned in Section 2. Roughly, lower flue gas temperature means higher efficiency. The variation of the flue gas temperature with time for different feeding systems is shown in Figure 4. The flue gas temperature for the top-fed boiler was about 110 °C and this value is approximately stable. Contrary to this, the flue gas temperature for the horizontal-fed boiler changes from approximately 138 °C to 160 °C.

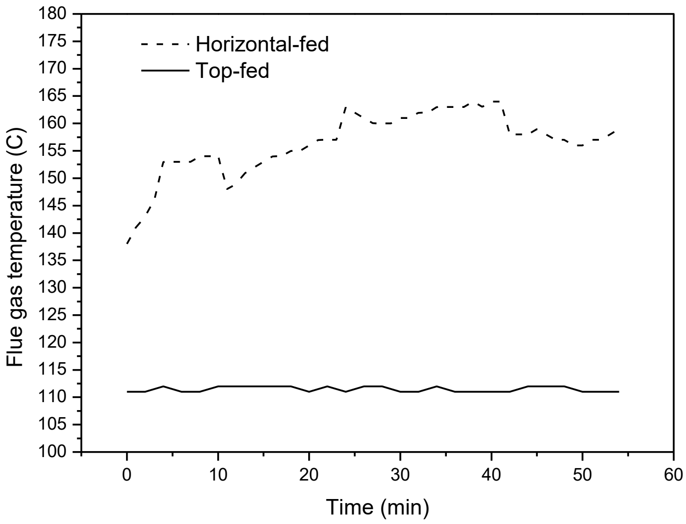

Figure 4. The change of flue gas temperatures with time for different feeding types

The change in thermal efficiency which calculated by indirect method with time is shown in Figure 5. When the thermal efficiencies are compared, it is seen that the top-fed boiler efficiency is between 93-94% with a time-averaged value of 93.5% and the horizontal-fed boiler efficiency is between 86-90% with a time-averaged value of 88.6. In the case of horizontal-fed, the system seems to be more unstable compared to top-fed. It can be said that this situation occurs due to problems such as agglomeration of the pellets and non-homogeneous combustion, especially in the case of horizontal-fed.

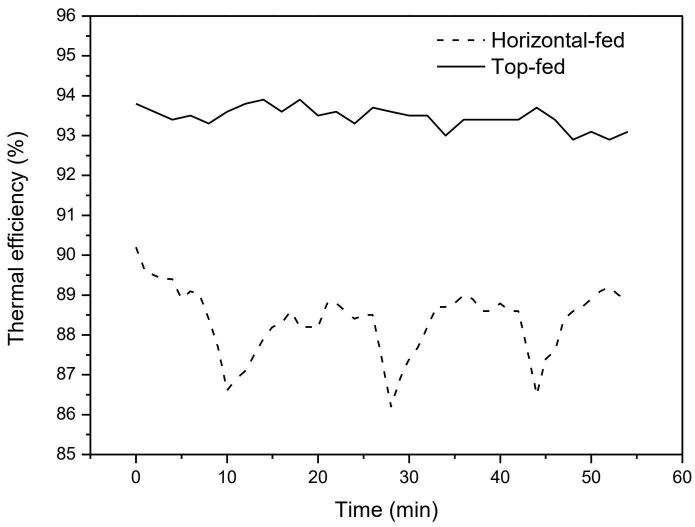

Figure 5. The change of thermal efficiencies with time for different feeding types

The average results of heat transfer to the water were given in Table 3. In both systems, the flow rates of the water were constant. Because of the different types of the boilers, temperature differences occurred and the heat transfer rates changed. The horizontal-fed boiler had lower heat transfer rate than the top-fed boiler. The time-averaged direct efficiency values for top-fed and horizontal-fed cases were 93.3% and 88.5%, respectively, which are slightly lower than indirect efficiencies. This is due to neglecting and not considering of unburned carbon and surface losses, respectively.

Table 3. Results obtained from the calorimeter device

Parameters	Horizontal-fed	Top-fed
Water flow rate (kg/s)	0.58	0.58
Inlet temperature of water (°C)	58.7	62.0
Outlet temperature of water (°C)	80.6	85.1
Temperature difference	21.9	23.1
Heat transfer to water (kW)	53.1	56.0
Direct thermal efficiency (%)	88.5	93.3

The variation of the O_2 and CO concentration with time for different feeding systems is shown in Figure 6 and Figure 7, respectively. From Figure 7, it is seen that in the top-fed situation there is less CO emission than the horizontal-fed situation. Also, CO emissions in the top-fed situation are more stable than in the horizontal-fed situation and do not change much with time. At top-fed case, the CO emissions were changing between 80-140 ppm, but at the horizontal-fed case, the CO emission values were fluctuating very much and the values were in the range of 100-2250 ppm. In the horizontal-fed case, pellet fuel is burned poorly. The reason for the poor combustion, could be that the pellet fuel does not mix well with the air. In addition, the more complicated flow which means more flue gas passes of the combustion products in the combustion chamber in relation to the top-fed case, as stated in properties of designed boilers, may have contributed to the unstabilties in the combustion process. It can be said that fluctuations in CO and O_2 emissions occurred due to problems such as agglomeration of the pellets and non-homogeneous combustion, especially in the case of horizontal-fed.

Also, it should be noted that a decrease in CO means that combustion improves, however as can be seen from the Equations 1 and 2, an increase in the amount of oxygen has a reducing effect on thermal efficiency.

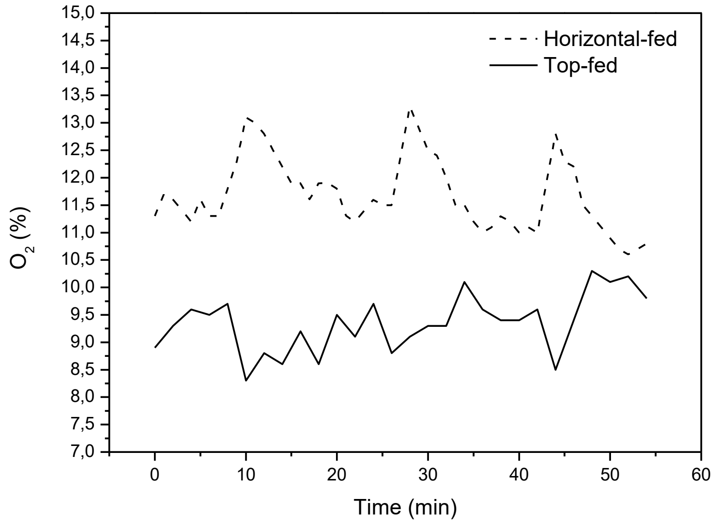

Figure 6. The variation of O_2 concentration with time for different feeding types

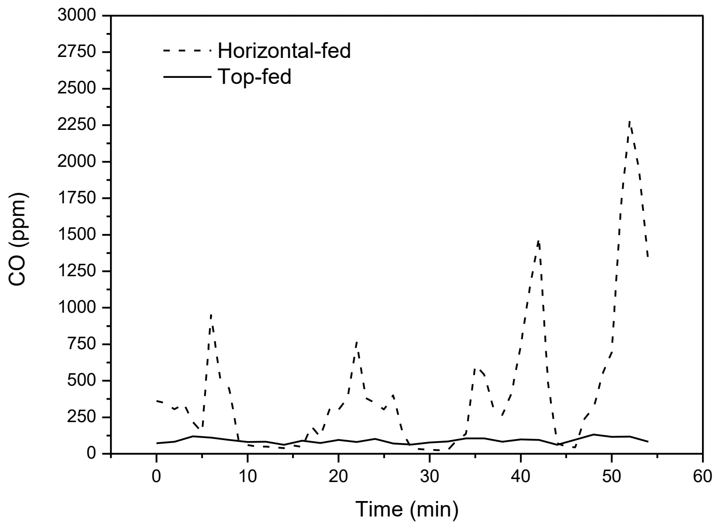

Figure 7. The variation of CO concentration with time for different feeding types

In combustion of hydrocarbon based fuels thermal (Zeldovich) and prompt (Fenimore) NO_x mechanisms are the most important mechanisms of NO_x production. An increase in oxygen concentration increased the rate of NO formation. It is also known that thermal NO formation mostly dependent on temperature (for every 90 °C temperature increase beyond 1927 °C) but independent of fuel type. The flame temperatures could not be measured in the experiments but in pellet combustion the flame temperatures were about 900-1300 °C which is ineffective in NO formation [13]. The variation of NO_x concentration with time is shown in Figure 8. This figure showed that the NO_x emissions from the top-fed are more stable and less than the horizontal-fed. NO_x emissions in the case of top-fed are around 100 ppm while NO_x emissions in the horizontal-fed are in the range of 150-200 ppm.

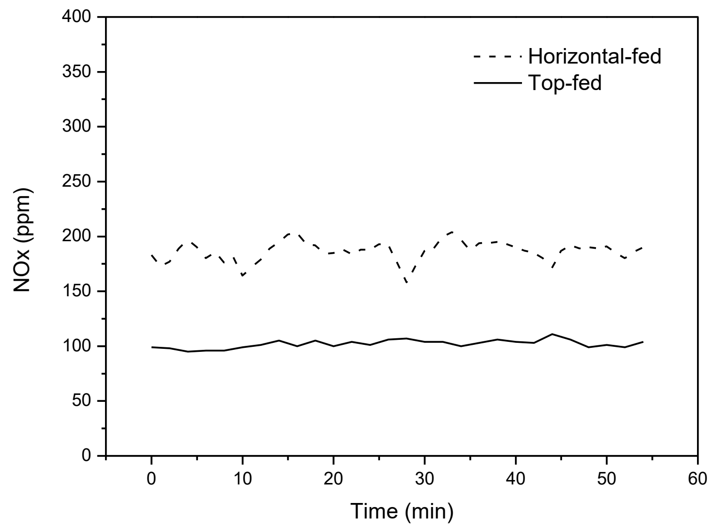

Figure 8. The variation of NO_x concentration with time for different feeding types

4. Conclusions

In this study, experiments were carried out under different feeding conditions with different flue gas outlet positions for two different pellet-fueled boilers. During the experiments, changes in CO and NO_x emissions, flue gas temperatures and thermal efficiencies were determined for each case. As a result of the experiments:

The top-fed boiler had higher thermal efficiency values as about 93-94%. In the horizontal-fed case, thermal efficiency value was approximately in the range of 86-90%. The flue gas temperatures in the top-fed boiler were 28-50 °C lower than in the horizontal-fed boiler. CO emissions in the top-fed situation were more stable than in the horizontal-fed situation and the change of CO with time is negligible. At top-fed case, the CO emissions were about 80-140 ppm, but at the horizontal-fed case, the CO emission values were fluctuating very much and were in the range of 100-2250 ppm. Similar to CO emissions, NOx emissions from the top-fed were more stable and less than the horizontal-fed which were around 100 ppm in the case of top-fed and 150-200 ppm in the horizontal-fed. The top-fed boiler had more stable combustion than the horizontal-fed boiler. The top-fed boiler performed higher performance characteristics compared to the horizontal-fed boiler. Thus, the top-fed boiler can be used instead of conventional solid fuel boilers for heating in residential buildings.

In the following periods, studies can be conducted on the effects of combustion chamber width, depth and length, smoke tube lengths, primary and secondary air rates on the performance of pellet fuel boilers.

Ethics in Publishing

There are no ethical issues regarding the publication of this study.

Acknowledgements

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