ACTA TECHNICA CORVINIENSIS – BULLETIN OF ENGINEERING
TOME XVI [2023] | FASCICULE 4 [OCTOBER – DECEMBER]

[1.] Mladen TOMIĆ, [2.] Predrag ŽIVKOVIĆ, [3.] Jovan ŠKUNDRIĆ,
[1.] Miroslav KLJAJIĆ, [1.] Borivoj STEPANOV, [1.] Željko VLAOVIĆ

PERFORMANCE ANALYSIS OF A BIOMASS–FIRED STEAM BOILER WITH FGR USING AGRICULTURAL RESIDUE STRAW AS FUEL

[1.] University of Novi Sad, Faculty of Technical Sciences, Trg Dositeja Obradovića 6, Novi Sad, SERBIA
[2.] University of Niš, Faculty of Mechanical Engineering, Aleksandra Medvedeva 14, Niš, SERBIA
[3.] University of Banja Luka, Faculty of Mechanical Engineering, Vojvode Stepe Stepanovića Blvd. Banja Luka, Banja Luka, BOSNIA & HERZEGOVINA

Abstract: This paper presents an analysis of a biomass–fired steam boiler with capacity of 14 MW which produces saturated steam at pressure of 14 bar using agriculture residue straw as fuel. The boiler operates with flue gas recirculation rate of 20%, a common technique to improve the efficiency of the combustion process and reduce emission. Data from the PLS sensors were collected to evaluate the boiler's performance. Thermal calculations were performed to analyze the heat transfer rate, heat loss, and combustion efficiency of the boiler. Three different cases were considered: flue gas recirculation after the bag filters, recirculation after the flue gas channel exit, and without the recirculation. Parallel, the emission of NOx for all scenarios was discussed. The analysis of the results shows that for both cases flue gas recirculation yields almost the same efficiency. However, the efficiency for lower flue gas recirculation is increased, and without flue gas recirculation was the highest according to both the model and calculations. This suggests that while flue gas recirculation can be an effective way to improve combustion efficiency and reduce emissions, it may not always be the most optimal solution. The findings of this study provide valuable insights into the biomass–fired steam boilers performance and the impact of flue gas recirculation on their efficiency and NOx emission. These insights can be useful for optimizing the design and operation of similar biomass–fired steam boilers and for promoting the use of renewable energy sources in industrial processes.
Keywords: biomass, FGR, NOx, steam boiler

INTRODUCTION

Steam boilers are widely used in various industries for producing steam, which is used for different purposes, such as power generation, heating, and industrial processes. Biomass steam boilers are one of the sustainable alternatives to fossil fuel boilers, and they have gained attention in recent years due to their potential to reduce greenhouse gas emissions and their low–cost fuel source [1].

The combustion of biomass in the boiler generates flue gases, which contain pollutants, including particulate matter (PM), sulphur dioxide (SO_2), nitrogen oxides (NO_x), and carbon monoxide (CO), which have adverse effects on the environment and human health [2,3]. The reduction of these emissions is of great importance, and the use of flue gas recirculation is a commonly used technique for this purpose.

Flue gas recirculation (FGR) is process where a part of the flue gas is returned to the combustion chamber to lower the combustion temperature. FGR is a possible way to improve combustion and decrease the emissions of carbon monoxide CO, particulate matter PM, and nitrogen oxides NOx in order to fulfil emission requirements, for NOx in [3]. The amount of flue gas recirculation depends on the boiler design, fuel characteristics, and emission regulations.

Summarized, the use of flue gas recirculation is commonly used technique to reduce emissions and increase the biomass steam boilers combustion efficiency [3,4].

In this paper, we investigate the performance of a 14 MW steam boiler which produces saturated steam at the pressure of 14 barg, which combusts agriculture residue straw, and operates with flue gas recirculation at a rate of 20%, working on 80% of the maximal power, i.e. 12.57 barg. The aim of this study is to compare the boiler efficiency with flue gas recirculation after the bag filters, flue gas recirculation after the exit from the flue gas channel, and without flue gas recirculation.

Data from PLS sensors, including temperatures at the steam generator furnace exit, after the water heater–economizer 4, and at the last flue gas channel exit, were utilized in this study. The excess air ratio calculation was enabled by measuring oxygen concentration at one point. Additionally, temperature after the bag filter, feed water, and water temperature after the economizer 4 were measured. The efficiency of the boiler was calculated for each case. The results indicated that the highest efficiency, according to both the model and calculations, was achieved without flue gas recirculation.

PERFORMANCE EVALUATION OF A BIOMASS–FIRED STEAM BOILER

Biomass is being combusted on a moving grate. The flue gases released transfer their heat to screens placed in the furnace. Downstream, the flue gases leave the furnace through an opening in the rear screen and enter the flue gas duct, which is inclined downward. Screen tubes are placed in the flue gas duct to transfer heat. After leaving the flue gas duct, the flue gases turn 180° and flow upward through a duct in which an evaporator and an economizer – ECO 4 are placed for heat exchange. After passing through ECO 4, the flue gases change direction again, flow downward, and transfer heat to the economizers ECO 3, ECO 2, and ECO 1 before leaving the flue gas duct and entering the cyclone and filter sections. Part of the flue gas is redirected back to the furnace for recirculation.

The stem boiler technical data are:

Boiler thermal power:

- 14 MW (saturated steam)

Water/steam parameters:

- working pressure – 14 bar
- feedwater temperature – 105°c
- saturated steam temperature – 195°c
- flue gas temperature at the boiler outlet: 170°C

Fuel type – Corn straw:

- LHV: 16 MJ/kg
- designed moisture content: 15%
- ash content on a dry mass: < 8%
- designed fuel ash melting point: < 750°c
- designed fuel nitrogen content: <0.3%
- designed fuel chlorine content: <0.3%
- designed fuel sulfur content: <0.1%

Based on the data provided for corn straw, its composition was adopted for the steam boiler thermal design. The calculations were carried out using the procedure described in various books on steam boiler thermal design [5–7].

These books provided the necessary equations and methodologies for determining the convective and radiant heat transfer coefficients in the steam boiler. The convective and radiant heat transfer coefficients are crucial parameters for evaluating the heat transfer process between the hot flue gases and the water/steam in the boiler. In the thermal design of steam boilers, it is important to accurately determine these coefficients to optimize the boiler's efficiency.

The criteria equations for convective heat transfer and radiant heat transfer were also compared in the calculation process. The results showed the difference < 10% between the criteria equations and also radiant heat transfer fluxes [5–8]. This indicates that methods provide accurate results and can be used interchangeably in the thermal design of steam boilers. However, it is important to note that the choice of the appropriate method may depend on the specific characteristics of the steam boiler and the operating conditions. Therefore, it is recommended to consult with experienced professionals in the field to select the most appropriate methodology of the steam boiler thermal design.

The adoption of air excess ratio is a crucial step of the steam boilers calculation. For the presented case, the excess air ratio was chosen according to the literature recommendations, which dictate a value of 1.2 in the furnace and 1.25 at the exit. The excess air ratio for the first flue gas channel was chosen to be equal to the value at the exit from the furnace, as determined by calculations. However, after the water heater economizer 4, the air excess ratio was found to be 1.345, and thus adopted as such in the calculation.

Similarly, for the two heat exchanger units further calculations were performed to determine the excess air ratio after the evaporator, economizer 3, and economizer 1. Assuming the same rate of growth, the excess air ratio was found to be 1.2975 after the evaporator, 1.3925 after economizer 3, and 1.4875 after economizer 1 at the exit. The excess air ratio was increased for 0.2 after the cyclone and filter to the value of 1.6875, in accordance with literature recommendations.

After thorough analysis and energy balance calculations, the flame adiabatic temperature was determined to be 1324°C. The temperature at the exit of the combustion chamber was found to be 744.6°C, which is consistent with previous findings in the literature. The temperature after economizer 4 was calculated at 366.3°C, and temperature at the exit from the flue gas channel at 181.5°C. These temperatures were calculated for each unit in the steam boiler, ensuring that the heat transfer energy balance between the heat exchanger and flue gases was within +–1%:

- for the flue gases

$$\dot{Q} = \dot{b} \cdot (I'' - I'), \qquad (1)$$

- for the heat exchanger

$$\dot{Q} = k \cdot F \cdot \Delta\theta, \qquad (2)$$

and in case of water heaters also the comparison with water side was considered:

$$\dot{Q} = \dot{m}_w \cdot c_w \cdot \Delta t_w. \qquad (3)$$

The comparison with provided data is presented in the following Figure 1 and Figure 2.

The average RMS between the calculated and the obtained data was found to be 33°C.

The water feed temperature adopted according to the available data was 105.3°C and the temperature at the Economizer 4 outlet was 191.5°C. The calculated water temperature at the economizer outlet (evaporator inlet) was 193.6°C of steam with quality of 0.4%. The difference occurs because in the moment for which the data were presented the water drum was filled to the required level, so the water flow was larger and valued 18.6 t/h. This gives the total heat power of the economizer line 1 to 4 of 1911 kW, compared to the calculated 1990 kW, which gives the total difference of 4%.

Figure 1. Temperature, pressure and mass flow readings

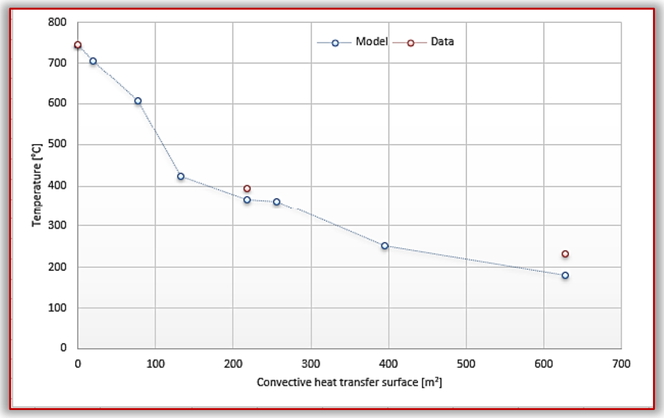

Figure 2. Comparison of temperature measurements and modelled temperatures

THE IMPACT OF FGR ON BOILER PERFORMANCE

The FGR technique involves the flue gas portion recirculation back to the combustion process. This results in a reduction of the flame temperature and the oxygen concentration, which leads to a decrease of the nitrogen oxides (NO_x) and other pollutants formation. However, this technique can also result in lower combustion efficiency, as the recirculated gas pollutes the combustion air and reduces the oxygen concentration.

According to the methodology presented above, the power and efficiency for the flue gas recirculation (FGR) from the filters and at the boiler outlet were calculated, as well as the case without FGR. In this analysis, the influence of the lower efficiency of the combustion process without FGR was considered. The results of the comparison are presented in the Table 1.

The calculations were performed with the methodology described above, and the results were compared for the cases with and without FGR. Table 1 shows that the power output and the efficiency were slightly lower for the FGR case, as expected. However, the difference in power output was only 1.5%, while the difference in efficiency was over the 4%. Temperatures at the combustion chamber and at the outlet are presented in the Table 2.

As expected, there is no significant difference for the cases where FGR is 20%. However, for reduced FGR, an increase in both efficiency and combustion temperature is observed.

Table 1. Thermal power in [kW] and the efficiency of steam boiler, in [%], for different scenarios

Exp no.	FGR– filter (20%)	FGR– exit (20%)	FGR– filter (10%)	Without FGR
Furnace	5670	5816	6421	6946
Exh. manif.	660	661	626	605
Flue gas ch.	968	962	866	755
Evaporator	1625	1613	1363	1146
Ecco 4	442	435	370	323
Turn chmb.	42	39	31	28
Ecco 3	977	950	844	750
Ecco 1–2	572	477	402	289
Net power	10996	10953	10924	10842
Eff.	84.4%	84.5%	86.6%	89.2%

Table 2. Adiabatic temperatures of the flame and flue gas temperature at the exit

Exp no.	FGR– filter (20%)	FGR– exit (20%)	FGR– filter (10%)	Without FGR
Adiabatic temp. of the flame	1324.31	1354.36	1440.50	1698.04
Flue gas temp. at the exit	182.0	185.5	166	170.0

NO_X FORMATION ANALYSIS

The concentration of "thermal NO_x" is controlled by the nitrogen and oxygen molar ratios and the combustion temperature. Combustion at temperatures well below 1,300°C forms much smaller ratios of thermal NO_x. For the obtained main species composition (N_2, H_2O, O_2, CO_2) the thermal equilibrium for NO_x is calculated for the adiabatic flame temperature. The concentration was calculated with help of Gasqe Chemical Equilibrium Software [9,10]. Gasqe is using the Lagrange Method of Undetermined Multipliers for minimization of the Gibbs free energy of the system to find the equilibrium state/ composition. Several different types of problems can be solved using this software from which the several different types of problem can be solved, from which the composition at a defined temperature and pressure was investigated.

The results presented in the Table 3 are in a good agreement with results of Sartor et al. [11] for small and medium sized combined heat and power biomass plants as they found emissions for wheat straw and whol crop to be in the range 500 to 1030 ppm, while for some biomass fuels it can be significantly over 1300 ppm. As it could be expected the higher temperatures lead to higher values and concentrations of NO_x in the combustion products.

Table 3. NOx concentration for different conditions per kg of fuel

Exp no.	FGR– filter (20%)	FGR– exit (20%)	FGR– filter (10%)	Without FGR
Adiabatic temp. of the flame	1324.31	1354.36	1440.50	1698.04
NOx [kmol/kg]	2.950e–4	3.064e–4	3.705e–4	6.466–4
r_{NOx}	9.71e–4	9.06e–4	1.24e–3	2.49e–3
r_{NOx} [ppm]	971	906	1240	2490

RESULTS AND DISCUSSION

To determine the optimum FGR rate, we need to consider both the boiler efficiency and NO_x emissions. Based on the efficiency the NO_x emissions decrease as the FGR rate increases.

To determine the optimum FGR rate, we need to consider both the boiler efficiency and NO_x emissions, with a weight of X given to NO_x emissions reduction. Based on the information available:

- Efficiency for FGR 0% = 89.2%,
- Efficiency for FGR 10% = 86.6%,
- Efficiency for FGR 20% = 84.4%.

This means that the efficiency decreases as the FGR rate increases.

NOx emissions for:

- FGR 0% = 6.466e–4 kmol/kg,
- FGR 10% = 3.705e–4 kmol/kg,
- FGR 20% = 2.950e–4 kmol/kg.

This means that the NO_x emissions decrease as the FGR rate increases.

To find the optimum FGR rate, we need to find the point at which the decrease in NO_x emissions balances out with the decrease in efficiency, with the (arbitrary) weight of 5 given to NO_x emission reduction relative to efficiency. We can calculate the weighted efficiency as:

Weighted Efficiency = Efficiency – (X · NO_x Emission Reduction),

where NO_x Emission Reduction is the relative reduction in NO_x emission compared to FGR 0%. For example, for FGR 10%:

NO_x Emissions Reduction = (NO_x Emissions for FGR 0% – NO_x Emissions for FGR 10%) / NO_x Emissions for FGR 0%.

As we can see from the table, the optimum FGR rate changes to 0% when using a weighted efficiency of 1. This means that if reducing NOx emissions is equally important as improving efficiency, then FGR should not be used at all. If we increase the weight for NOx reduction to 5, the highest weighted efficiency is still achieved at 0% FGR rate, but the difference between the weighted efficiency at 0% and 10% FGR rate has decreased compared to the previous table.

Table 4. Analysis of FGR Rate on NOx Emissions and Efficiency, with Weighted Reductions 1

FGR Rate	NOx Emissions [kmol/kg]	Efficiency	NOx Emissions Reduction	Weighted Efficiency
0%	6.466–4	89.2%	89.2%	89.2%
10%	3.705e–4	86.6%	81.3%	–4.7%
20%	2.950e–4	84.4%	73.2%	–26.8%

Table 5. Analysis of FGR Rate on NOx Emissions and Efficiency, with Weighted Reductions 5

FGR Rate	NOx Emissions [kmol/kg]	Efficiency	NOx Emissions Reduction	Weighted Efficiency
0%	6.466–4	89.2%	0%	89.2%
10%	3.705e–4	86.6%	42.6%	81.3%
20%	2.950e–4	84.4%	54.4%	79.3%

CONCLUSIONS

Flue gas recirculation (FGR) is an effective and cost–efficient technique for reducing NOx emissions from burners in certain applications. It is predicted that recirculating up to 20% of the flue gases through the burner can reduce NOx emissions by as much as 55%. However, this may also reduce the steam boiler's efficiency by almost 5%. To determine the optimum FGR rate, an analysis was performed to find the point at which the decrease in NOx emissions is balanced with the decrease in efficiency.

The analysis revealed that the FGR rate should be around 10% depending on the weight of emissions compared to efficiency. It is worth noting, though, that this analysis is based on a simplified model, and the actual optimal FGR rate may vary depending on the specific conditions of the boiler and local emission regulations. If energy stability is a priority, then higher efficiency is preferred over NOx emissions.

Nomenclature

$\dot{b}$	fuel flow, [kg·s^{-1}]
c_w	water heat capacity, [J·kg^{-1}·K^{-1}]
F	heat transfer area, [m^2]
I	flue gas enthalpy per kg of fuel, [kJ·kg^{-1}]
k	overall heat transfer coefficient, [W·m^2·K^{-1}]
$\dot{m}_w$	water mass flow rate, [kg·s^{-1}]
t_w	water temperature, [°C].
Δθ	log mean temperature difference, [K].

Acknowledgement

The authors would like to express their sincere gratitude to Mr. Rade Đurić and Mr. Vladan Petrović for their invaluable contribution to this study. Their generous provision of data, including temperature measurements was crucial to the successful completion of this research.

Note: This paper was presented at DEMI 2023 – 16th International Conference on Accomplishments in Mechanical and Industrial Engineering, organized by Faculty of Mechanical Engineering, University of Banja Luka (BOSNIA & HERZEGOVINA), co–organized with the Faculty of Mechanical Engineering University of Niš (SERBIA), Faculty of Mechanical Engineering University of Podgorica (MONTENEGRO), Faculty of Engineering Hunedoara, University Politehnica Timișoara (ROMANIA) and Reykjavik University (ICELAND), in Banja Luka (BOSNIA & HERZEGOVINA), in 01–02 June, 2023

References

[1] Transparency Market Research. From: https://www.globenewswire.com/news–release/2023/01/09/2584969/0/en/Biomass–Boiler–Market–to–grow–at–a–CAGR–of–18–1–during–the–forecast–period–from–2022–to–2031–TMR–Study.html, accesed on: April 25, 2023.

[2] Monks, P. et al., (2017). The Potential Air Quality Impacts from Biomass Combustion. Department for Environment, Food and Rural Affairs; Scottish Government; Welsh Government; and Department of the Environment in Northern Ireland, UK.

[3] Polonini, L.F., Petrocelli, D., Lezzi, A.M. (2023). The Effect of Flue Gas Recirculation on CO, PM and NOx Emissions in Pellet Stove Combustion. Energies, vol. 16, no. 2, p. 954–954

[4] Caposciutti, P., et al. (2022). An Experimental Investigation on the Effect of Exhaust Gas Recirculation in a Small–Scale Fixed Bed Biomass Boiler, Chemical Engineering Transactions, vol. 92, p. 397–402.

[5] Brkić, Lj., Živković, T. (1987). Termički proračun parnih kotlova. Mašinski fakultet Beograd.

[6] Bogner, M. (2004). Termotehničar. AGM, Beograd.

[7] Đurić, V., Farmakoski V. (1958). Parni kotlovi –deo I. Naučna Knjiga, Beograd.

[8] Radojković N., Ilić, G., Vukić, M., Stojanović, I., Živković P. (2007). Termodinamika II. Mašinski fakultet Niš, Niš.

[9] Morley Chris. Gaseq. From: http://www.gaseq.co.uk/, accessed on: April 25, 2023.

[10] Tomić, M. et al., The pollutant emissions assessment from personal vehicles in the republic of Serbia, 1st International conference on advances in science and technology – COAST 2022, Herceg Novi, Montenegro, p. 248 – 254.

[11] Sartor, K. et al. (2014). Prediction of SO_x and NO_x emissions from a medium size biomass boiler. Biomass and Bioenergy, vol. 65, p. 91 – 100

ISSN: 2067–3809