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Optimizing Flue Gas Recirculation for Enhanced Efficiency in Biomass-Fired Boilers: A Comprehensive Study

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Abstract As sustainable energy practices become more popular, biomass-fired boilers are becoming a choice over traditional fossil fuel models due to their eco-friendly nature. Despite their environmental advantages, biomass boilers still emit pollutants like particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NO_X), and carbon monoxide (CO), posing environmental concerns. To mitigate these emissions, modern biomass-fired boilers often incorporate Flue Gas Recirculation (FGR). This research focuses on a 14 MW biomass-fired boiler operating with a 20% FGR rate, examining three scenarios: two with varying FGR levels and one without FGR. The analysis reveals a connection between emission reduction via FGR and boiler efficiency maintenance. Additionally, it suggests optimizing FGR levels to boost boiler efficiency. The study presents a comprehensive approach to effectively implement FGR in biomass-fired boilers while ensuring acceptable efficiency levels. NO_X emissions were analyzed using combustion simulation software and the Zeldovich method to estimate thermal NO_X production.

Keywords: Gas Mixture, Real Gases, Temperature-Dependent, Viscosity.

1. Introduction

Steam boilers play a vital role in diverse industries, providing steam for various applications such as power generation, heating, and industrial processes. With a growing emphasis on sustainability, biomass steam boilers have emerged as an eco-friendly alternative to conventional fossil fuel boilers. These biomass boilers have gained attention due to their potential to reduce greenhouse gas emissions and their use of cost-effective biofuels [1]. However, burning biomass in these boilers leads to flue gases containing pollutants such as particulate matter (PM), sulphur dioxide (SO_2), nitrogen oxides (NO_X), and carbon monoxide (CO), raising environmental and health concerns [2,3]. To address these emissions, techniques like flue gas recirculation (FGR) have gained traction.

FGR involves reintroducing a portion of flue gas into the combustion chamber to moderate the combustion temperature. It has emerged as a viable strategy to improve combustion efficiency and reduce the release of CO, PM, and NOx, ensuring compliance with emission standards [3]. The implementation of FGR depends on factors like boiler design, fuel characteristics, and emission regulations.

Essentially, FGR has become a widespread method to concurrently reduce emissions and enhance the combustion efficiency of biomass steam boilers [3,4]. This study focuses on the operational performance of a 14 MW steam boiler designed to generate saturated steam at a pressure of 13 barg, utilizing agricultural residue straw as its primary fuel source. The boiler incorporates a flue gas recirculation system operating at a 20% recirculation rate, functioning at 80% of its maximum capacity, corresponding to 12.57 barg.

This research aims to evaluate the efficiency and NO_X emissions of the 14 MW steam boiler under varying parameters, specifically focusing on FGR and its impact on combustion efficiency and pollutant emissions. To achieve this, comprehensive data from process and temperature sensors were utilized. These sensors measured temperatures at critical points within the boiler system, including the steam generator furnace exit, downstream of water heater-economizer 4, and the terminal point of the flue gas channel. Oxygen concentration measurements determined excess air ratios, while temperature readings post-bag filter, feed water, and downstream of economizer 4 were analyzed. The study meticulously calculated both the boiler's efficiency and NO_X emissions for each scenario. Intriguingly, the findings revealed a distinct pattern where the absence of FGR resulted in the highest efficiency but also the highest NO_X emissions, consistent with modeling predictions and calculations

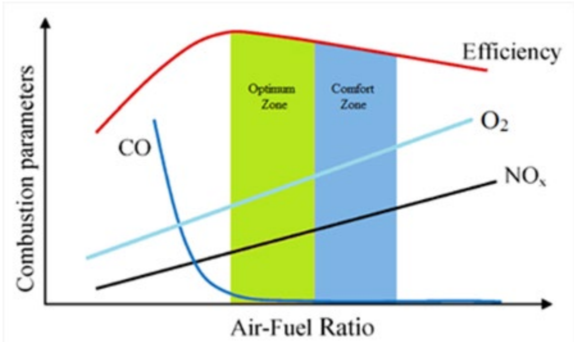

Figure1 Influence of combustion parameters on efficiency and pollutant emission

The subsequent Results and Discussion section explored the influence of flue gas extraction points on NOX production. It was found that this parameter had limited significance, with both Gaseq and Zeldovich methods indicating increased emissions with decreasing FGR rates. However, the Zeldovich method provided a more realistic representation of NO_X emissions compared to Gaseq's thermal equilibrium results. The study recommended an optimal FGR rate of around 10% to balance boiler efficiency and NO_X emissions, aiming for an emission level of approximately 300 mg/MJ, considering that most NO_X emissions originate from thermal NO_X.

Acknowledging that empirical data could significantly enhance the credibility of the conclusions drawn, the study emphasized the importance of empirical insights and experimental validation in refining the precision and applicability of the research outcomes. In summary, this study sheds light on the complex relationship between heat transfer, combustion efficiency, and pollutant emissions in a biomass-fired steam boiler. The systematic approach toward thermal design, performance analysis, and evaluating FGR's impact on NO_X emissions provides valuable insights for advancing biomass combustion technology.

2. Thermal Design and Performance Analysis of a Biomass Steam Boiler

Biomass undergoes combustion on a moving grate within the steam boiler system. The released flue gases transfer their heat to screens positioned in the furnace. Following this, the flue gases exit the furnace through an opening in the rear screen and enter an inclined downward flue gas duct. Within this duct, screen tubes aid in the transfer of heat. After passing through this duct, the flue gases make a 180° turn and ascend through a duct containing an evaporator and an economizer (ECO 4) for heat exchange. Subsequently, the flue gases alter their direction, descending to transfer heat to economizers ECO 3, ECO 2, and ECO 1 before leaving the flue gas duct and entering the cyclone and filter sections. A fraction of the flue gas is redirected back to the furnace for recirculation.

The technical specifications of the steam boiler are as follows:

- Boiler thermal power: 14 MW (producing saturated steam);
- Water/steam parameters:
    - Working pressure: 14 bar;
    - Feedwater temperature: 105°C;
    - Saturated steam temperature: 195°C;
- Flue gas temperature at boiler outlet: 170°C;
- Fuel type: Corn straw:
    - Lower Heating Value (LHV): 16 MJ/kg;
    - Designed moisture content: 15%;
    - Ash content on 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%.

The thermal design of the steam boiler was based on the specific characteristics of corn straw, forming the foundation for all calculations. Procedures outlined in authoritative literature regarding steam boiler thermal design [5-7] were meticulously followed throughout the process. These foundational texts provided a plethora of equations and methodologies crucial for understanding convective and radiant heat transfer coefficients essential to the boiler's operation. These coefficients are vital for understanding the complex heat exchange dynamics between the heated flue gases and the water/steam inside the boiler. Accurately determining these coefficients is crucial as they form the basis for optimizing the boiler's efficiency.

In pursuit of precision, comparative analyses were conducted between criteria equations governing convective and radiant heat transfer, revealing discrepancies below 10%. Notably, this margin remained consistent across both convective and radiant heat transfer fluxes [5-8]. This convergence of results underscores the accuracy of these methodologies, suggesting their interchangeability in steam boiler thermal design. However, it's important to acknowledge that the choice of methodology may depend on the specific characteristics of the steam boiler and its operating parameters. Therefore, seeking guidance from experienced experts in the field is prudent to judiciously select the optimal thermal design methodology for the given steam boiler.

Integral to the calculations is determining the air excess ratio, a step of utmost importance. In line with established literature guidelines, the excess air ratio for the presented scenario was determined as 1.2 within the furnace and 1.25 at the exit. Similarly, the excess air ratio downstream of water heater economizer 4 was calculated as 1.345 and used for subsequent calculations. Likewise, additional computations were carried out to determine the excess air ratios post-evaporator, economizer 3, and economizer 1. Assuming a consistent growth rate, the computed excess air ratios were 1.2975 post-evaporator, 1.3925 after economizer 3, and 1.4875 following economizer 1 at the exit. Adhering to authoritative recommendations, an incremental increase of 0.2 was applied post cyclone and filter, resulting in an excess air ratio of 1.6875.

The culmination of comprehensive analysis and diligent energy balance computations led to the determination of the flame adiabatic temperature, which remained constant at 1324°C. Notably, there was a significant congruence with the temperature at the exit of the combustion chamber, aligning seamlessly with previous literature findings. Further calculations yielded a temperature of 366.3°C following economizer 4, while the exit temperature from the flue gas channel was measured 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

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

for the heat exchanger:

$$\dot{Q} = k \cdot F \cdot \Delta\theta, \tag{2}$$

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

$$\dot{Q} = \dot{m}_w \cdot c_w \cdot \Delta t_w. \tag{3}$$

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

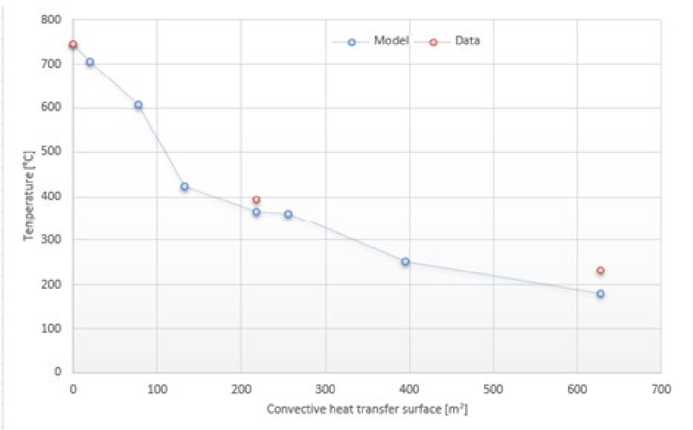

Figure 2. Comparison of temperature measurements and modelled temperatures

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%.

3. Impact of Flue Gas Recirculation on Boiler Performance

The Flue Gas Recirculation (FGR) technique reintroduces a portion of the flue gas back into the combustion process. This action reduces the flame temperature and oxygen concentration, subsequently decreasing the formation of nitrogen oxides (NO_X) and other pollutants. However, while this method curtails emissions, it can also diminish combustion efficiency by contaminating the combustion air and reducing oxygen levels.

In accordance with the aforementioned methodology, calculations were conducted for power and efficiency considering FGR from the filters and at the boiler outlet, alongside a scenario without FGR. This analysis factored in the influence of reduced combustion efficiency without FGR. Table 1 illustrates the comparative results.

Utilizing the methodology outlined earlier, the results were juxtaposed between cases with and without FGR. As depicted in Table 1, the FGR scenario exhibited lower power output and efficiency, aligning with expectations. Remarkably, the power output difference was marginal, standing at only 1.5%. In contrast, the efficiency disparity exceeded 4%. Detailed temperatures from the combustion chamber and the outlet are provided in Table 2.

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

Location	FGR - (20%)	FGR - (10%)	Without FGR
Furnace	5670	6313	6946
Exh. manif.	660	470	605
Flue gas ch.	968	866	755
Evaporator	1625	1363	1146
Ecco 4	442	370	323
Turn chmb.	42	31	28
Ecco 3	977	844	750
Ecco 1-2	572	402	289
Net power	10996	10923	10842
Eff.	84.4%	86.6%	89.2%

4. NO_X Formation Analysis

The concentration of "thermal NO_X" hinges on the nitrogen and oxygen molar ratios and the combustion temperature. Combustion occurring well below 1,300°C results in notably reduced levels of thermal NO_X. To assess NOx emissions, a two-pronged method was employed.

Initially, the Gaseq software was utilized, employing the Lagrange Method of Undetermined Multipliers. This facilitated the calculation of average temperatures within the combustion chamber [9,10]. Gaseq's approach, rooted in minimizing the Gibbs free energy of the system, enabled investigation into the composition at specific temperatures and pressures, crucially informing the thermal conditions governing combustion. This software provided insights into the equilibrium state/composition for main species (N_2, H_2O, O_2, CO_2), subsequently deriving NO_X thermal equilibrium at the chamber's average temperature.

Utilizing the Zeldovich mechanism at the combustion region, an estimation of NO_X concentration in the products becomes feasible. Simplifying this approach allows for deriving the rate of NO production [11,12,13,14]:

$$\frac{d[NO]}{dt} \approx 2 \cdot k_{f,1} \cdot [O] \cdot [N_2], \tag{4}$$

where the concentrations are in [mol·cm-3], T is the temperature in K, [O] is the concentration of atomic oxygen. Further, the formation of free oxygen atoms could be obtained as following [14]:

$$[O] = 3.97 \cdot 10^5 \cdot T^{-0.5} \cdot [O_2]^{0.5} \exp\left(\frac{-31090}{T}\right), \tag{5}$$

where the concentrations are in [mol·cm-3]. An alternative method to presented in the eq. (11) is presented by the following expression [14]:

$$[O] = 36.64 \cdot 10^5 \cdot T^{0.5} \cdot [O_2]^{0.5} \exp\left(\frac{-27123}{T}\right), \tag{6}$$

which generally leads to a bit higher partial O-atom concentration.

The methodology for determination of coefficients $k_{f,1}$ was chosen according to comparison between results of measurements presented in the [15] and coefficients presented in the paper [16]:

$$k_{f,1} = 1.473 \cdot 10^{13} \cdot \exp\left(\frac{-315000}{R_u T}\right), \tag{7}$$

and eq. (6).

The NO_X obtained by the model gives the production rate is in the range from 800, 21, and 18 mg_{NOx} per MJ for 0, 10 and 20% of FGR respectively which is generally the same order of magnitude with IPCC specific emission factors [17,18]. On the other hand, method presented on the basis of Gaseq software gave the concentrations order of magnitude higher than expected.

Table 2. Adiabatic temperatures of the flame and flue gas temperature at the exit and NOx production rate [17]

Exp no.	FGR (20%)	FGR (10%)	Without FGR
Adiab. temp. of the flame	1324	1501	1698
Flue gas temp. - chamber exit	745	746	736
Aver. flue gas temp. comb. cham.	1002	1071	1137
Flue gas temp. at the exit	182.0	166	170.0
NO_x prod. rate [$kmol \cdot m^{-3} \cdot s^{-1}$]; Gaseq	5.32e-6	9.64e-6	16.1e-6
NO_x prod. rate [$kmol \cdot m^{-3} \cdot s^{-1}$]; Model	1.86e-7	1.23e-7	4.9e-6

5. Conclusions

This study extensively investigated the thermal design and performance analysis of a steam boiler using corn straw biomass as fuel. The intricate dynamics of heat transfer within the boiler system were meticulously assessed, considering the unique characteristics of the fuel and operational parameters. Adopted thermal design methods, drawn from authoritative literature, facilitated the determination of essential convective and radiant heat transfer coefficients critical for enhancing boiler efficiency. Comparative analyses validated the interchangeability of criteria and radiant heat transfer coefficients in steam boiler thermal design.

Key technical details of the steam boiler were presented, encompassing critical parameters like thermal power, water/steam conditions, flue gas properties, and fuel composition, serving as the groundwork for subsequent analyses.

The investigation deeply explored the impact of Flue Gas Recirculation (FGR) on boiler performance. While FGR showed potential in reducing nitrogen oxide (NO_X) emissions, it was observed to possibly decrease combustion efficiency due to diluted combustion air and reduced oxygen levels. Calculations under different scenarios revealed a marginal decrease in power output (1.5%) and a more significant decline in efficiency (over 4%) with FGR implementation.

A comprehensive examination of NO_X formation employed both Gaseq software and the Zeldovich extended method. The Zeldovich method demonstrated higher accuracy and alignment with anticipated values, in contrast to Gaseq's consistently high emission predictions. A suggested NO_X emission target of approximately

300 mg/MJ was proposed, recommending a maximum FGR rate of around 10% to achieve this goal. The study emphasized the importance of empirical data for model validation, enhancing the reliability and practicality of the drawn conclusions.

In summary, this study highlighted the intricate relationships among heat transfer, combustion efficiency, and pollutant emissions in a biomass-fired steam boiler. The systematic approach to thermal design, performance analysis, and the assessment of FGR's impact on NO_X emissions provided comprehensive insights into the boiler's behavior, offering avenues for further enhancements in biomass combustion technology.

References

[1] ***, Transparency Market Research, Biomass Boiler Market, https://www.transparencymarketresearch.com/industrial-biomass-boiler-market.html
[2] Monks, P. *et al*., 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, 2017.
[3] Polonini, L. F., Petrocelli, D., Lezzi, A. M., The Effect of Flue Gas Recirculation on CO, PM and NOx Emissions in Pellet Stove Combustion, *Energies*, *16* (2023), 2, pp. 1-16
[4] Caposciutti P., *et al*., An Experimental Investigation on the Effect of Exhaust Gas Recirculation in a Small-Scale Fixed Bed Biomass Boiler, *Chemical Engineering Transactions*, *92* (2022), pp. 397-402
[5] LJ. Brkić, T. Živković, Termički proračun parnih kotlova. Mašinski fakultet Beograd. Beograd, Yugoslavia, 1987.
[6] Bogner, M., Termotehničar, AGM, Beograd, Yugoslavia, 2004.
[7] Đurić, V., Farmakoski, V., Parni kotlovi -deo I., Naučna Knjiga, Beograd, Yugoslavia, 1958.
[8] Radojković, N., Ilić, G., Vukić, M., Stojanović, I., Živković, P., Termodinamika II. 2nd ed., Mašinski fakultet Niš, Niš, Serbia, 2007
[9] Chris, M., Gaseq, 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, Proceedings, 1st International conference on advances in science and technology – COAST 2022, Herceg Novi, Montenegro, 2022, pp. 248 – 254
[11] Lalić, B., Poljak, A., Radica, G., Mišura, A., Low-Speed Marine Diesel Engine Modeling for NO_X Prediction in Exhaust Gases, *Energies*, *14* (2021) 15, pp. 4442
[12] Wang, Y., Liu, J., Wang, L., Zaiguo, F.U., Weng, P., Thermal Calculations and NO_X Emission Analysis of a Micro Gas Turbine System Without a Recuperator, *Thermal Science*, 26 (2022) 5A, pp. 3817-3829
[13] Weisser, G.A., Modelling of Combustion and Nitric Oxide Formation for Medium-Speed DI Diesel Engines: A Comparative Evaluation of Zero and Three-Dimensional Approaches, Ph. D. thesis, ETH Swiss Federal Institute of Technology, Zürich, Switzerland, 2001
[14] ***, https://www.afs.enea.it/project/neptunius/docs/fluent/html/th/node420.htm#Missaghi90
[15] Cellek, M.S., Pınarbasi, A., Investigations on Performance and Emission Characteristics of An Industrial Low Swirl Burner While Burning Natural Gas, Methane, Hydrogen-Enriched Natural Gas and Hydrogen as Fuels, *International Journal of Hydrogen Energy*, *43* (2018) 2, pp. 1194-1207
[16] Parra, C.A.F., Heat Transfer Investigations in a Modern Diesel Engine, Ph.D. thesis, University of Bath Department of Mechanical Engineering, Bath, UK, 2008
[17] Bhatt, A. *et al*., Emission factors of industrial boilers burning biomass-derived fuels, *Journal of the Air & Waste Management Association*, *73* (2023) 4, pp. 241-257
[18] ***, Netherlands Environmental Assessment Agency/Milieu en Natuur Plan Bureau, https://www.rivm.nl/bibliotheek/digitaaldepot/BOLK_I_biomass_Final.pdf