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ENHANCING EMISSION REDUCTION AND EFFICIENCY IN BIOMASS STEAM BOILERS THROUGH FGR: EXAMINING NOX PRODUCTION AND OPERATIONAL DYNAMICS

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Abstract: As a result of efforts to follow sustainable development trends in thermal energy, the increasing utilization of biomass-fired boilers is notable as an environmentally acceptable alternative to conventional fossil fuel-based designs. However, while more ecologically viable, biomass boilers still emit specific pollutants, with particulate matter (PM), sulfur dioxide (SO_2), nitrogen oxides (NOx), and carbon monoxide (CO) being the major concerns. To mitigate these emissions, modern biomass-fired boilers often incorporate Flue Gas Recirculation (FGR). This study examines a 14 MW biomass-fired boiler with a 20% FGR rate. Analysis encompasses three scenarios: two FGR levels and operation without FGR. The research reveals a complex interdependence between emissions reduction through FGR and boiler efficiency. Moreover, findings suggest justified reduction in FGR levels to enhance boiler efficiency. The study presents a comprehensive plan for efficient FGR implementation in biomass-fired boilers while maintaining acceptable efficiency levels. For NOx emissions analysis, combustion simulation software and the Zeldovich method were employed to estimate thermal NOx production.

Keywords: biomass, efficiency, FGR, NOx, steam boiler.

1. INTRODUCTION

Steam boilers play a crucial role across diverse industries by generating steam for a wide array of applications, including power generation, heating, and industrial processes. As the imperative for sustainable practices intensifies, biomass steam boilers have emerged as an environmentally friendly alternative to conventional fossil fuel boilers. These biomass boilers have garnered substantial attention for their potential to curtail greenhouse gas emissions and their utilization of cost-effective biofuels [1]. However, the combustion of biomass within these boilers gives rise to flue gases containing pollutants such as particulate matter (PM), sulphur dioxide (SO_2), nitrogen oxides (NO_X), and carbon monoxide (CO), posing environmental and health concerns [2,3]. In this context, the imperative to mitigate these emissions has sparked widespread interest in techniques like flue gas recirculation (FGR).

Flue gas recirculation (FGR) involves the reintroduction of a portion of flue gas back into the combustion chamber to temper the combustion temperature. FGR has emerged as a viable strategy to enhance combustion efficiency and ameliorate the release of carbon monoxide CO, particulate matter PM, and nitrogen oxides NOx, thereby ensuring compliance with emission standards [3]. The extent of FGR implementation is contingent upon variables like boiler design, fuel characteristics, and prevailing emission regulations.

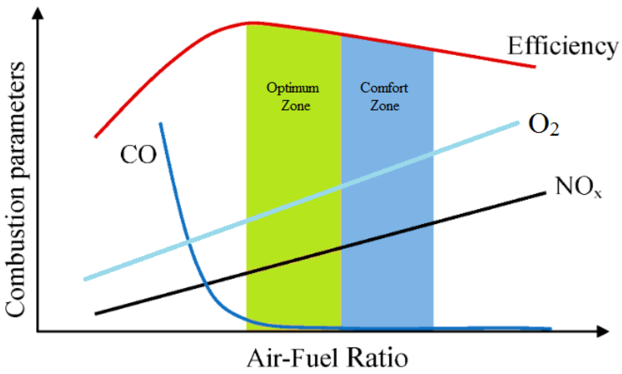

Figure 1. *Influence of combustion parameters on efficiency and pollutant emission*

In essence, the utilization of flue gas recirculation has become a ubiquitous means to concurrently mitigate emissions and augment the combustion efficiency of biomass steam boilers [3,4]. The present study delves into 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. Notably, the boiler is equipped with 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 endeavor aims to assess the efficiency and NO_X emissions of a 14 MW steam boiler under varying parameters, specifically focusing on flue gas recirculation (FGR) and its impact on combustion efficiency and pollutant emissions. To achieve this objective, a comprehensive dataset from process and temperature sensors was utilized. These sensors facilitated temperature measurements at critical points within the boiler system, including the steam generator furnace exit, downstream of the water heater-economizer 4, and the terminal point of the flue gas channel. Oxygen concentration measurements were used to determine excess air ratios, while temperature readings post-bag filter, feed water, and downstream of economizer 4 were incorporated for analysis. The research meticulously calculated both the boiler's efficiency and NO_X emissions for each scenario. Intriguingly, the findings underscored a distinct pattern wherein the absence of flue gas recirculation resulted in the highest efficiency, albeit also leading to the highest NO_X emissions. These outcomes were consistent with both modeling predictions and calculations.

In the subsequent Results and Discussion section, the study explored the influence of flue gas extraction points on NO_X production. The analysis revealed that this parameter had limited significance, with both Gaseq and Zeldovich methods indicating a trend of elevated emissions with decreasing FGR rates. Notably, the Gaseq software exhibited consistently higher emission levels than the Zeldovich extended method, often deviating from expected values. The study found that the Zeldovich method offered a more realistic representation of NO_X emissions compared to Gaseq's thermal equilibrium results. The optimal FGR rate was determined based on a balance between boiler efficiency and NO_X emissions, recommending an emission level of around 300 mg/MJ. Given that the majority of NO_X emissions stem from thermal NO_X, a suggested FGR rate of around 10% was proposed, which could be adjusted to a lower threshold with increasing boiler efficiency.

It is acknowledged that integrating empirical data for model calibration and validation could significantly enhance the credibility and robustness of the conclusions drawn. The study then concludes by emphasizing 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 intricate relationship between heat transfer, combustion efficiency, and pollutant emissions in a biomass-fired steam boiler. The systematic approach taken towards thermal design, performance analysis, and the evaluation of FGR's impact on NO_X emissions offers valuable insights for enhancing biomass combustion technology.

2. 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%

The thermal design of the steam boiler was predicated on the compositional attributes of corn straw, which served as the basis for the calculations. The procedures outlined in authoritative literature concerning steam boiler thermal design [5-7] were meticulously employed throughout the calculations. These foundational texts provided a wealth of equations and methodologies pivotal for discerning convective and radiant heat transfer coefficients intrinsic to the steam boiler's functionality. Such coefficients play a pivotal role in elucidating the intricate heat exchange dynamics between the heated flue gases and the water/steam within the boiler. Accurate determination of these coefficients assumes paramount significance, forming the bedrock upon which the boiler's efficiency optimization rests.

In the pursuit of precision, comparative analyses were conducted between the criteria equations governing convective and radiant heat transfer, revealing discrepancies below 10%. Notably, this margin was consistently maintained across both criteria and radiant heat transfer fluxes [5-8]. The confluence of outcomes underscores the accuracy of these methodologies, suggesting their interchangeability in the thermal design of steam boilers. However, it is pivotal to recognize that the choice of methodology might hinge upon the specific attributes of the steam boiler and its operational parameters. As such, it is prudent to solicit guidance from seasoned experts within the domain to judiciously select the optimal thermal design methodology for the given steam boiler.

Integral to the calculations is the determination of the air excess ratio, a step of cardinal import. In accordance with established literature directives, the excess air ratio for the presented scenario was ratified as 1.2 within the furnace and 1.25 at the exit. Similarly, the excess air ratio post the water heater economizer 4 was discerned at 1.345 and subsequently adopted for calculations. Analogously, for the ensuing heat exchanger units, supplementary computations were executed to ascertain the excess air ratios post-evaporator, economizer 3, and economizer 1. Conjecturing a consistent growth rate, the computed excess air ratios stood at 1.2975 post-evaporator, 1.3925 after economizer 3, and 1.4875 subsequent to economizer 1 at the exit. Conforming to authoritative recommendations, an incremental shift of 0.2 was applied post the cyclone and filter, culminating in an excess air ratio of 1.6875.

The culmination of comprehensive analysis and diligent energy balance computations culminated in the determination of the flame adiabatic temperature, which stood resolute at 1324°C. Noteworthy congruence emerged with the temperature at the exit of the combustion chamber, aligning seamlessly with antecedent literature findings. Further computations furnished the temperature following economizer 4, gauged at 366.3°C, while the exit temperature from the flue gas channel materialized 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. 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%.

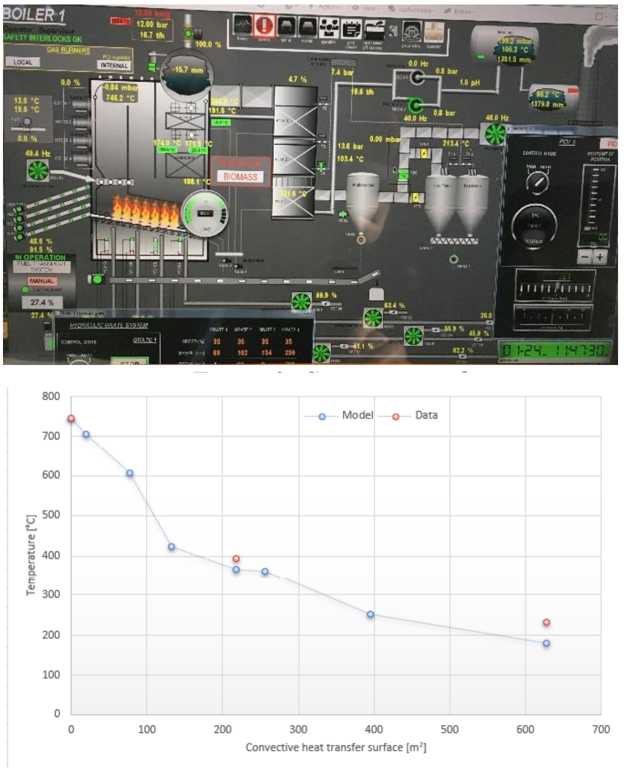

Figure 2. *Comparison of temperature measurements and modelled temperatures*

3. 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 (NOX) 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 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.

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 NOx" 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. In the assessment of NO_X emissions, a dual-method approach was employed. The first methodology involved the utilization of Gaseq software, enabling the calculation of average temperatures within the combustion chamber [9,10]. Gaseq 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. This provided crucial insights into the thermal conditions governing the combustion process. For the obtained main species composition (N_2, H_2O, O_2, CO_2) the thermal equilibrium for NO_X is calculated for the average temperature in the combustion chamber.

In the second approach, a partition of the boiler into distinct zones was enacted. The initial zone encapsulated temperatures surpassing 1,300°C, while the subsequent zone encompassed temperatures below 1,300°C, extending until the point of exit from the combustion chamber. Within this framework, the focal point was the computation of the NO_X formation rate. This rate was meticulously evaluated and subsequently averaged across the entirety of the combustion chamber's volume. By partitioning the boiler into these designated zones and calculating the averaged NO_X formation rate, a comprehensive assessment was achieved, elucidating the intricate relationship between temperature gradients and nitrogen oxide production in the combustion process. Studies show that nitrogen oxides (NO_X) are mostly formed during the diffusion period of combustion, but to a lesser extent during the homogeneous combustion phase.

Using the Zeldovich mechanism, one can estimate the concentration of NO_X in the products. By simplifying, we can derive the rate of NO production as follows [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]:

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

and eq. (6).

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
Adiabatic temp. of the flame	1324	1501	1698
Flue gas temp. at the chamber exit	745	746	736
Average flue gas temperature in comb. cham.	1002	1071	1137
Flue gas temp. at the exit	182.0	166	170.0
NO_x prod. rate [kmol·m^{-3}·s^{-1}] Gaseq	5.32e-6	9.64e-6	16.1e-6
NO_x prod. rate [kmol·m^{-3}·s^{-1}] Model	1.86e-7	1.23e-7	4.9e-6

The NOX 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.

5. RESULTS AND DISCUSSION

The investigation into the influence of flue gas extraction point on NOx production revealed that this parameter had limited significance. Both the Gaseq and Zeldovich methods indicated a trend of increasing emissions with a reduction in Flue Gas Recirculation (FGR) rate. The Gaseq software, simulating thermal equilibrium of products, consistently demonstrated emission levels that were notably higher than those obtained using the Zeldovich

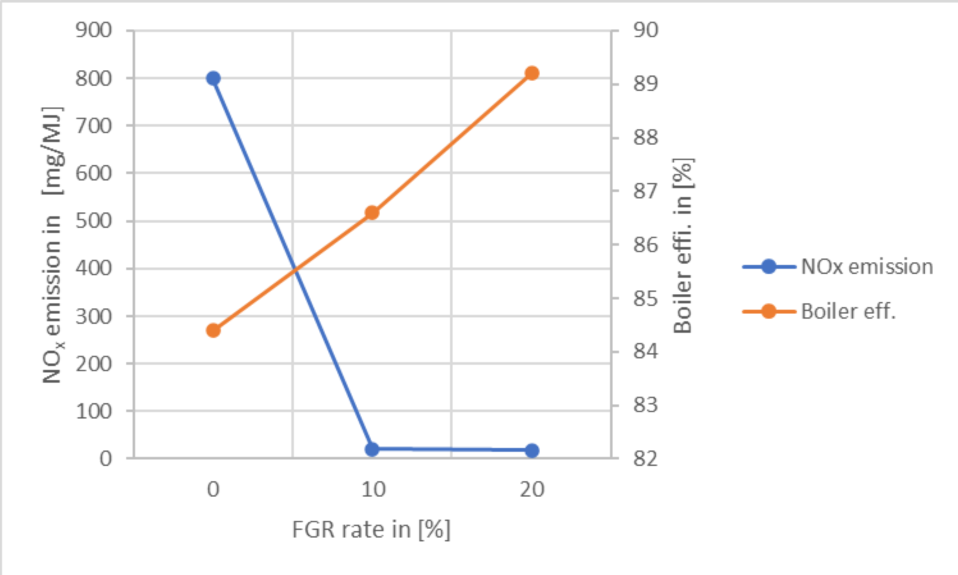

Figure 3. *Combustion parameters in the function of air-fuel ratio*

extended method. Moreover, these Gaseq-generated values consistently deviated from the expected levels, aligning only at elevated temperatures.

In light of these findings, it is the consensus of the authors that the Zeldovich method provides a more realistic representation of NOX emissions as compared to the thermal equilibrium results offered by the Gaseq software.

To ascertain the optimal FGR rate, a dual consideration of boiler efficiency and NO_X emissions is necessary. Notably, an emission level of approximately 300 mg/MJ appears to be a reasonable target. Given that the predominant portion of NOx emissions (90-95%) originates from thermal NO_X, it is recommended to cap the FGR rate at around 10%. This recommendation may even lean towards a lower threshold when the boiler efficiency surpasses 86.6%, approaching the vicinity of 87%.

It is imperative to acknowledge that the reliability and quality of these conclusions could be substantially enhanced with the integration of empirical data for model calibration and validation. Such experimental insights would further refine the accuracy and robustness of the outcomes.

6. CONCLUSIONS

In this study, the thermal design and performance analysis of a steam boiler combusting corn straw biomass were thoroughly examined. The intricate heat transfer dynamics within the boiler system were meticulously evaluated, taking into account the specific attributes of the fuel and operational parameters. The adopted thermal design methodologies, derived from authoritative literature, facilitated the determination of convective and radiant heat transfer coefficients, fundamental for optimizing boiler efficiency. Comparative analyses demonstrated a high degree of congruence between criteria and radiant heat transfer coefficients, validating their interchangeability in steam boiler thermal design.

Key technical data of the steam boiler were presented, encompassing parameters such as thermal power, water/steam conditions, flue gas characteristics, and fuel composition. These parameters served as the foundation for subsequent analyses.

The impact of Flue Gas Recirculation (FGR) on boiler performance was meticulously investigated. The FGR technique, though capable of mitigating nitrogen oxide (NO_X) emissions, was also observed to potentially lower combustion efficiency due to diluted combustion air and reduced oxygen concentration. Calculations considering various scenarios indicated a marginal reduction in power output (1.5%) and a more substantial reduction in efficiency (over 4%) when FGR was implemented.

An exhaustive analysis of NO_X formation was conducted, employing both the Gaseq software and the Zeldovich extended method. The Zeldovich method exhibited superior accuracy and alignment with expected values, contrasting with Gaseq's consistently high emissions predictions. A recommended NO_X emission level of around 300 mg/MJ was proposed, with the FGR rate recommended to be capped at approximately 10% to achieve this target. The importance of empirical data for model validation was emphasized, as it would enhance the reliability and applicability of the conclusions drawn.

In summary, this study underscored the intricate interplay of heat transfer, combustion efficiency, and pollutant emissions within a biomass-fired steam boiler. The methodical approach to thermal design and performance analysis, coupled with the evaluation of FGR impact on NO_X emissions, provides a comprehensive understanding of the boiler's behavior and paves the way for further optimizations in biomass combustion technology.

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8. REFERENCES

[1] Transparency Market Research, 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] P. Monks, *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] L.F. Polonini, D. Petrocelli, A.M. Lezzi, *The Effect of Flue Gas Recirculation on CO, PM and NOx Emissions in Pellet Stove Combustion*, Energies, Vol. 16-2 (2023). 954-954. https://doi.org/10.3390/en16020954

[4] P. Caposciutti, et al., *An Experimental Investigation on the Effect of Exhaust Gas Recirculation in a Small-Scale Fixed Bed Biomass Boiler*, Chemical Engineering Transactions, Vol. 92 (2022) 397-402. https://doi.org/10.3303/CET2292067

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

[6] M. Bogner, *Termotehničar*. *AGM*, Beograd, 2004.

[7] V. Đurić, V. Farmakoski, *Parni kotlovi -deo I*. Naučna Knjiga, Beograd, 1958.

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

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

[10] M. Tomić, *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, 248 – 254.

[11] B. Lalić, A. Poljak, G. Radica, A. Mišura, A., *Low-Speed Marine Diesel Engine Modeling for NO_X Prediction in Exhaust Gases*, Energies, Vol. 14-15 (2021) 4442. https://doi.org/10.3390/en14154442

[12] Y. Wang, J. Liu, L. Wang, F.U. Zaiguo, P. Weng, P., *Thermal Calculations and NO_X Emission Analysis of a Micro Gas Turbine System Without a Recuperator*, Thermal Science, Vol. 26-5A (2022) 3817-3829. https://doi.org/10.2298/TSCI210601336W

[13] G. A. Weisser, *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.

*** https://www.afs.enea.it/project/neptunius/docs/fluent/html/th/node420.htm#Missaghi90

[14] M. S. Cellek, A. Pınarbasi, *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, Vol. 43-2 (2017) 1194-1207. https://doi.org/10.1016/j.ijhydene.2017.05.107

[15] C. A. F. Parra, *Heat Transfer Investigations in a Modern Diesel Engine,* Ph.D. thesis, University of Bath Department of Mechanical Engineering, Bath, UK, 2008

*** https://www.nrel.gov/docs/fy23osti/83308.pdf

*** https://www.rivm.nl/bibliotheek/digitaaldepot/BOLK_I_biomass_Final.pdf

СМАЊЕЊЕ ЕМИСИЈЕ И ПОВЕЋАЊЕ ЕФИКАСНОСТИ ПАРНОГ КОТЛА ПОСРЕДСТВОМ РЕЦИРКУЛАЦИЈЕ ДИМНОГ ГАСА: ГЕНЕЗА NOX-а И ДИНАМИКА РАДА

Сажетак: Као резултат настојања да се прате трендови одрживог развоја у термоенергетици, све је чешћа примјена и парних котлова на биомасу, као еколошки прихватљиве алтернативе конвенционалним конструкцијама на фосилна горива. Ипак, иако еколошки далеко прихватљивији, и котлови на биомасу такође емитују одређене полутанте, од којих су највећи проблем свакако честице (PM), сумпор-диоксид (SO_2), оксиди азота (NOx) и угљен-моноксид (CO). У циљу смањења поменуте штетне емисије, у раду савремених парних котлова се, између осталог, примјењује и тзв. рециркулација димних гасова (FGR). У овом раду је разматран парни котао на биомасу snage 14 MW са стопом FGR од 20%. Анализа је спроведена за три различита сценарија и то два различита нивоа FGR-а и рад без FGR-а. Током истраживања, уочена је веома сложена зависност између смањења емисија посредством FGR-а и ефикасности самог парног котла. Штавише, резултати истраживања указују и на оправданост евентуалног смањења нивоа FGR-а како би се повећала ефикасност котла, а сама студија нуди свеобухватан план за ефикасну примјену FGR-а у парним котловима на биомасу уз одржавање ефикасности на прихватљивом нивоу. У оквиру истраживања емисије NOx-а коришћен је софтвер за симулацију сагоријевања, као и метод Зелдовича за процјену продукције термалног NOx-а.

Кључне ријечи: биомаса, ефикасност, FGR, NOx, парни котао.

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