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Study on condensing boiler technology potential accounting various fuels

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Abstract

Condensing boilers represent now the most advanced technology in boilers field. Currently, their operation is almost entirely based on natural gas, which mostly consists of methane (typically more than 95 % in volumetric composition). When natural gas is not available – for example when there is no access to the natural gas network – the usual alternative is LPG. Liquid fuel is also taken into account in some studies. The energy saving potential by harnessing the latent heat of water vapors from flue gas is analyzed in the paper for another seven fuels – butane, propane, coal gasification gas, biogas, heavy fuel oil, diesel and bio-oil – and the reference fuel is methane. The greenhouse impact of these fuels is also analyzed. The study indicates that biogas offers the highest energy saving potential for condensing technology (even higher than methane) while heavy fuel oil has the lowest potential. Evaluation of CO_2 emissions shows that coal gasification gas has the greatest greenhouse impact.

Keywords: Condensing boiler; fuels; combustion; efficiency; pollution.

1. Introduction

Condensing technology currently offers the highest level of performance in boilers field. The idea of this technology is the condensation of the vapors of water contained in the flue and recovery of the latent heat, as indicated in Fig. 1. Thus, efficiency may increase with 10 to 12 % in the case of the gas-fired condensing boilers compared with gas-fired conventional boilers [1, 2]. The yield depends on the return water temperature (the lower the temperature, the higher

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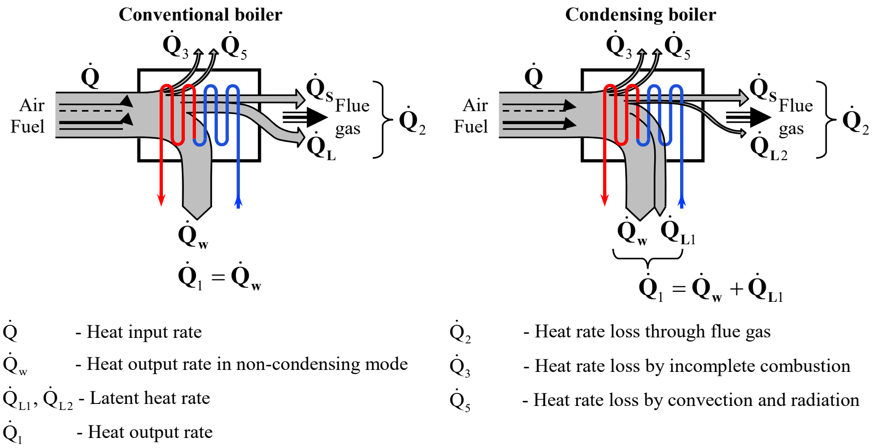

Fig. 1. Principle of condensing technology.

the yield is [3]), which varies during the heating season; the study in [4], performed in typical conditions for central Russia, shows that condensing boilers usually operate at optimal temperature regime (in condensing regime) only 30 - 60 % of the entire operating time in the heating season. Taking into consideration boiler efficiency at full load and the average value of the return water temperature during the heating season, one can predict seasonal efficiency of the condensing boiler, as indicated in [5].

For a certain heat output, higher efficiency offered by condensing technology with respect to traditional (non-condensing) technology involves lower fuel consumptions. Thereby, NOx and CO emission levels are lower. The study in [6] shows that the environmental impact of condensing gas-fired boilers is roughly 23 % lower (on average) than the impact of their traditional counterparts. Beside the lower fuel consumption, the advanced combustor solutions used on condensing boilers have a significant contribution to the lower emissions. The premixed combustor analyzed in [7] is such a solution. Due to the use of throttle body and metal fiber, NOx and CO emissions of this combustor proved to be less than 11 ppm and 50 ppm, respectively, under equivalence ratios in the range 0.724-0.795.

Condensing technology is typically associated with condensing boilers used in central or domestic heating system. This is not quite right. In fact, condensing technology refers to any application implying the recovery of waste energy from flue in such extent that flue gas temperature decreases below the dew point of water vapors and condensation occurs. The usual solution involves the introduction of an additional heat exchanger after a traditional boiler, in the flue gas flow. The additional heat exchanger can be a water preheater, a combustion air preheater or can be the link between the flue gas duct and an absorption heat pump (the heating solution is a hybrid one in this case). In most cases, the additional heat exchanger is used as water preheater, in heating systems (central or domestic), as discussed in [8]. A designing and optimizing method for condensing finned tubes heat exchanger is presented in [9]. The case study in [10], referring to a central heating system of 40 MW, shows that cash return period for an additional heat exchanger operating in condensing mode is 5-7 years whether the material used is stainless steel or 2 years whether the construction material is carbon steel coated with polypropylene. The case in which the additional heat exchanger is an air preheater is analyzed in [11]. It is shown that the air preheater can increase efficiency with 5 % above the efficiency of condensing boilers since the low temperature of air in the cold season (considered to be 0 °C in the study) may reduce temperature of flue gas down to 27.5 °C. A hybrid heating system consisting of a traditional boiler connected with a heat pump via an additional heat exchanger was analyzed in [12] and proved to be a reliable solution.

All the studies presented above refer to units operating with natural gas. Condensing technology also includes LPG fired boilers (conversion from natural gas to LPG usually implies some minimal corrections – e.g. change of gas nozzles and readjustment of the burner inlet fuel pressure), liquid fuel-fired boilers and even pellet-fired boilers; the experimental study presented in [13], indicates a thermal efficiency of 95 % for a pellet fired condensing boiler.

Besides, technical implications of the natural gas enrichment with hydrogen on condensing boiler performance was theoretically investigated in [14] and performance of condensing boilers operating with bituminous coal was analyzed in [15], being estimated a thermal efficiency of roughly 105 %. In this background, the objective of the current study was evaluation of the potential and characteristics of the condensing technology for an enlarged category of fuels.

2. Methodology

The study was performed accounting the gaseous and liquid fuels depicted in table 1 and table 2. The volumetric composition of coal gasification gas and the chemical compositions of heavy fuel oil (HFO) and diesel were assumed from [16]. Volumetric composition of biogas (from anaerobic digestion) and chemical composition of bio-oil (from pyrolysis of sugar cane straw) were assumed from [17] and [18], respectively. The reference fuel is methane (G20).

Table 1. Volumetric composition of the gas fuels considered in the study.

Fuel	CO, %	CO_2, %	H_2, %	CH_4, %	C_3H_8, %	C_4H_{10}, %	O_2, %	N_2, %
Methane (G20)	-	-	-	100	-	-	-	-
Butane (G30)	-	-	-	-	-	100	-	-
Propane (G31)	-	-	-	-	100	-	-	-
Coal gasification gas	24.2	8.9	16.8	2.9	0.2	0.1	0.2	46.7
Biogas	-	25	15	60	-	-	-	-

Table 2. Chemical composition of the liquid fuels considered in the study, mass percent.

Fuel	C, %	H, %	O, %	N, %	S, %	A, %	W, %
HFO	87.2	11.2	0.3	0.2	0.6	0.2	0.3
Diesel	86.5	12.6	0.3	0.1	0.3	0.2	-
Bio-oil	57.5	7	33.8	1	0.1	0.6	-

Taking into account the components reacting with oxygen, the Gross Calorific Value (GCV) of the gaseous and liquid fuels, in kJ/Nm^3 and kJ/kg, respectively, were calculated. This parameter represents the total amount of heat released when 1 kg or 1 Nm^3 of fuel is completely burned and considering that water vapors formed in combustion process are entirely condensed; thus, the quantity of heat (latent heat) contained in this water vapor is recovered. The calculation formulas used are [19]

$$GCV = 126.44 \cdot CO + 127.7 \cdot H_2 + 398.58 \cdot CH_4 + 1018.23 \cdot C_3H_8 + 1340.19 \cdot C_4H_{10}, \quad (1)$$

$$GCV = 339 \cdot C + 1256 \cdot H - 109 \cdot (O - S), \quad (2)$$

where CO, H_2, H_2S, C_mH_n and O_2 are the components of the gaseous fuel (carbon monoxide, hydrogen, hydrogen sulfide, hydrocarbons and oxygen), in percent (volumetric composition), while C, H, S and O are the mass percentages of carbon, hydrogen, sulfur and oxygen in the liquid fuel.

Combustion chemistry was treated according to [19]. Theoretical amount of oxygen for the combustion of gaseous and liquid fuels, in Nm^3/Nm^3 of fuel and in Nm^3/kg of fuel, were expressed as

$$V_{O2} = \frac{1}{100} \cdot \left[0.5 \cdot CO + 0.5 \cdot H_2 + 1.5 \cdot H_2S + \sum \left(m + \frac{n}{2} \right) \cdot C_mH_n - O_2 \right], \quad (3)$$

$$V_{O2} = 0.01 \cdot \left(1.867 \cdot C + 5.6 \cdot H + 0.7 \cdot S - 0.7 \cdot O\right). \tag{4}$$

By taking into account the conventional volumetric percentage of oxygen in the air (21 %) and the average moisture content of the ambient air of 0.0161 Nm^3/Nm^3 of dry air, the amount of combustion air was expressed as

$$V_a^0 = \frac{1.0161}{0.21} \cdot V_{O2} \text{ – theoretical,} \tag{5}$$

$$V_a = AER \cdot V_a^0 \text{ – real,} \tag{6}$$

where AER is the air excess ratio.

Amount of the flue gas was expressed as

$$V_{fg} = V_{CO2} + V_{SO2} + V_{N2} + V_{H2O}^0 + 1.0161 \cdot \left(AER - 1\right) \cdot V_a^0 , \tag{7}$$

where V_{CO2}, V_{SO2} and V_{N2} are the amounts of carbon dioxide, sulfur dioxide and nitrogen in flue gas while V_{H2O}^0 is the theoretical amount of water vapors in flue gas. For gaseous fuels, these amounts were calculated as

$$V_{CO2} = \frac{1}{100} \cdot \left(CO + CO_2 + \sum m \cdot C_m H_n\right); \tag{8}$$

$$V_{SO2} = \frac{H_2 S}{100}; \tag{9}$$

$$V_{N2} = 0.79 \cdot V_a^0 + \frac{N_2}{100}; \tag{10}$$

$$V_{H2O}^0 = \frac{1}{100} \cdot \left(H_2 + H_2 S + \sum \frac{n}{2} \cdot C_m H_n\right) + 0.0161 \cdot V_a^0 . \tag{11}$$

In the case of liquid fuels, the amounts of the flue gas components were calculated as

$$V_{CO2} = 1.867 \cdot \frac{C}{100}; \tag{12}$$

$$V_{SO2} = 0.7 \cdot \frac{S}{100}; \tag{13}$$

$$V_{N2} = 0.79 \cdot V_a^0 + 0.8 \cdot \frac{N}{100}; \tag{14}$$

$$V_{H2O}^0 = 11.2 \cdot \frac{H}{100} + 1.244 \cdot \frac{W}{100} + 0.0161 \cdot V_a^0 . \tag{15}$$

In formula (15), W is the mass percentage of water in the fuel.

The amount of water in the flue gas, in Nm^3/Nm^3 of fuel or in Nm^3/kg of fuel, was expressed as

$$V_{H2O} = V_{H2O}^{0} + 0.0161 \cdot (AER - 1) \cdot V_{a}^{0} . \tag{16}$$

For a relevant analysis of the potential and benefits of the condensing technology for each of the considered fuels, the amounts of combustion air, flue gas and water content in the flue gas were expressed with reference to the heat input ensured by the burner of the boiler and calculated on GCV basis. Thus, the real volumetric flow rates of combustion air, CO_2, flue gas and water content in the flue gas, in Nm^3/h, expressed as

$$\dot{V}_a = 3600 \cdot V_a \cdot FC; \quad \dot{V}_{CO2} = 3600 \cdot V_{CO2} \cdot FC; \quad \dot{V}_{fg} = 3600 \cdot V_{fg} \cdot FC; \quad \dot{V}_{H2O} = 3600 \cdot V_{H2O} \cdot FC , \tag{17}$$

were divided to the heat input rate, which is expressed in kW and is given by

$$\dot{Q} = FC \cdot GCV . \tag{18}$$

Thus, after simplifying fuel consumption (FC), expressed in kg/s or Nm^3/s, the specific volumetric flow rates of combustion air, flue gas and water content in the flue gas, expressed in $(Nm^3/h)/kW$, were obtained as

$$V_{a\,hi} = 3600 \cdot \frac{V_a}{GCV}; \quad V_{CO2\,hi} = 3600 \cdot \frac{V_{CO2}}{GCV}; \quad V_{fg\,hi} = 3600 \cdot \frac{V_{fg}}{GCV}; \quad V_{H2O\,hi} = 3600 \cdot \frac{V_{H2O}}{GCV} . \tag{19}$$

Specific mass flow rate of water content in the flue gas, in (kg/h)/kW, was expressed as

$$m_{H2O\,hi} = \rho_{N\,H2O} \cdot V_{H2O\,hi} , \tag{20}$$

where $\rho_{N\,H2O} = 0.805\ kg/Nm^3$ is the density of water vapors in normal condition.

By multiplying each of the three specific parameters from formulas (19) and (20) with the heat input rate (which is known in any particular application), the volumetric and mass flow rates are obtained, in Nm^3/h and kg/h, respectively. Hence, comparative analysis on the condensing technology characteristics can be performed on the basis of these flow rates when one takes into account several fuels in any particular application.

3. Results and discussions

The parameters defined by formulas (1) - (20) were calculated for all the gaseous and liquid fuels indicated in table 1 and table 2. The values of gross calorific value, theoretical amount of the combustion air and the real amounts of combustion air, CO_2, flue gas and water in the flue gas are presented in table 3. It should be noted that was assumed AER = 1.25 in all cases.

Table 3. Characteristic parameters for the analyzed fuels.

Fuel	GCV [kJ/Nm^3] or [kJ/kg]	V_a^0	V_a	V_{CO2}	V_{fg}	V_{H2O}
		[Nm^3/Nm^3 of fuel] or [Nm^3/kg of fuel]				
Methane (G20)	39858	9.67	12.09	1.00	13.09	2.19
Butane (G30)	148208	35.07	43.83	4.00	46.58	6.19
Propane (G31)	101823	24.18	30.23	3.00	32.23	4.48
Coal gasification gas	6699	1.34	1.68	0.37	2.01	0.27
Biogas	25830	6.17	7.71	0.85	8.64	1.47
HFO	43673	10.92	13.65	1.63	14.29	1.47
Diesel	45161	11.23	14.04	1.61	14.74	1.63
Bio-oil	24624	5.95	7.44	1.07	8.07	0.90

The specific volumetric flow rates of combustion air and flue gas as well as the specific mass flow rate of water content in the flue gas are presented in Fig. 2, Fig. 3 and Fig. 4 for all the analyzed fuels.

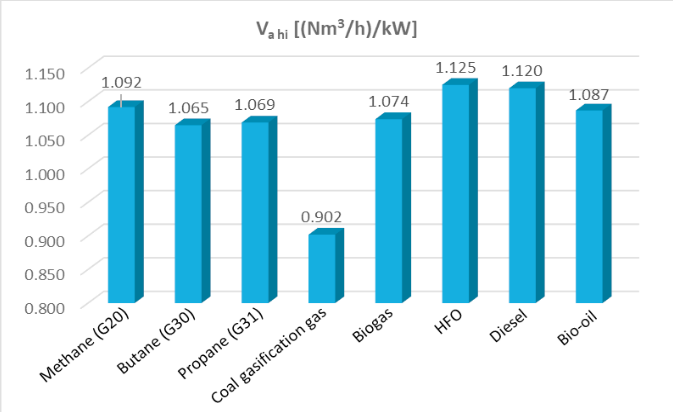

Fig. 2. Specific volumetric flow rates of combustion air.

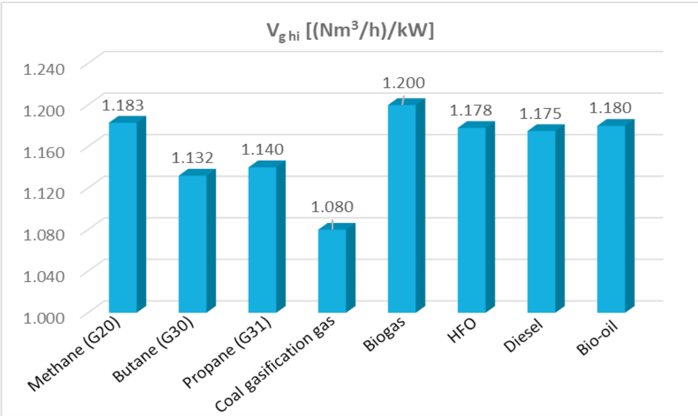

Fig. 3. Specific volumetric flow rates of flue gas.

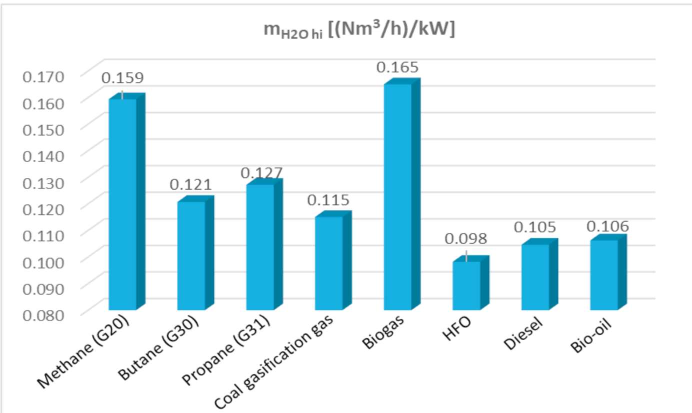

Fig. 4. Specific mass flow rate of water content in the flue gas.

As Fig. 2 indicates, HFO requires the highest amount of combustion air, which is 3.02 % higher than in the case of the reference fuel (methane). The lowest amount of combustion air is lower with 19.82 % than the highest one and corresponds to coal gasification gas. The current air blowers for condensing boilers may ensure rated air flow rates in larger ranges, so the total flexibility of gas or liquid fuel-fired condensing boiler to fuel change can be ensured by properly choosing the air blower and by adjusting the rated air flow rate function by fuel. As an example, the rated volumetric air flow of a condensing boiler with 25 kW rated heat input rate (one of the most common in Romania), which are in the range 22.55 to 28.13 Nm^3/h for the analyzed fuels (see table 4), can be all ensured by the air blower FIME PX 118. Obviously, conversion from gaseous to liquid fuel operation or vice versa requires more complex measures beside the air blower adjustment since the fuel supply systems of the two fuel types are completely different.

The highest specific volumetric flue gas flow rate is produced by the biogas combustion and is 1.44 % higher than in the case of the methane combustion (see Fig. 3). The lowest specific volumetric flue gas flow rate is 10 % lower and corresponds to the coal gasification gas.

The highest specific mass flow rate of water content in the flue gas also corresponds to biogas combustion (see Fig. 4). This flow rate is 3.53 % higher than in the case of methane combustion. Accordingly, the highest amount of latent heat of water vapors from flue gas can be harnessed when biogas is used as fuel in a condensing boiler (or in any other application involving condensing technology), so biogas offers the highest energy saving potential by harnessing the latent heat. Obviously, the benefits of condensing technology could be maximum in this case. Referring to a condensing boiler with 25 kW heat input and operating with biogas, the mass flow rate of water vapors in flue gas is 4.13 kg/h (see table 4). In real operating conditions, condensing boilers always operate with partial condensation (condensation is never complete), so condensate flow rate is lower than mass flow rate of water vapors in flue gas.

Table 4. Characteristic parameters for the analyzed fuels in the case of a condensing boiler of 25 kW heat input.

Fuel	$V_{a,25kW}$ [Nm^3/h]	$V_{CO2,25kW}$ [Nm^3/h]	$V_{fg,25kW}$ [Nm^3/h]	$m_{H2O,25kW}$ [kg/h]
Methane (G20)	27.3	2.25	29.58	3.98
Butane (G30)	26.63	2.68	28.3	3.02
Propane (G31)	26.73	2.65	28.5	3.18
Coal gasification gas	22.55	4.98	27	2.88
Biogas	26.85	2.95	30	4.13
HFO	28.13	3.35	29.45	2.46
Diesel	28	3.23	29.38	2.62
Bio-oil	27.18	3.93	29.5	2.66

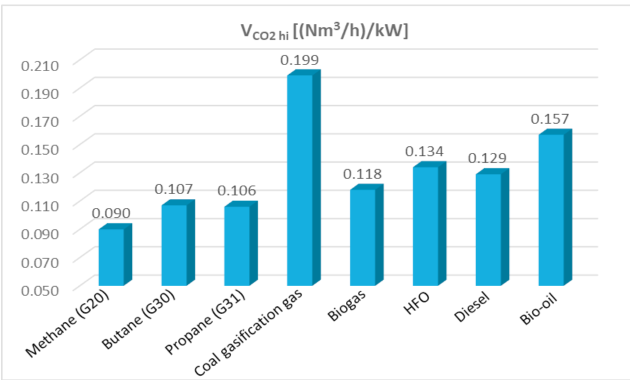

Fig. 5. Specific volumetric flow rates of CO_2 in the flue gas.

The lowest mass flow rate of water content (with 41.92 % lower than the maximum one, corresponding to biogas combustion) is produced when HFO is burned. A theoretical mass flow rate of condensate of 2.46 kg/h could be produced in the case of a HFO-fired condensing boiler of 25 kW heat input. Accordingly, the benefits of condensing technology (energy saving potential by harnessing the latent heat) are minimum in this case.

Specific volumetric flow rates of CO_2 in flue gas are shown in Fig. 5. It can be seen that all seven analyzed fuels have greater greenhouse impact than methane (the reference fuel) since their CO_2 emissions are higher. Coal gasification gas has the greatest impact (CO_2 emissions are 2.21 times higher than in the case of methane) while propane has the lowest impact (with 17.78 % higher than methane).

4. Conclusions

The study shows that the difference between the specific volumetric flow rates of combustion air is maximum 19.82 % (1.125 Nm^3/kWh vs. 0.902 1.125 Nm^3/kWh) for any two out of the seven analyzed fuels. Hence, conversion of a condensing boiler from one fuel to another (both gaseous or both liquid) does not require the change of the air blower (the most expensive component of the air and gas streams) if the blower is properly chosen. In fact, conversion implies only adjustment of the fuel supply system or/and replacement of nozzles, which involves minimum costs. This is an important advantage from technic-economic point of view since offers flexibility to select the most convenient fuel and to change it when another fuel becomes more convenient.

From all the analyzed fuels, biogas has the highest energy saving potential by harnessing the latent heat of the water vapors in flue gas. The flow rate of water vapors content in the flue gas of biogas (which is the maximum possible flow rate of condensate) is 3.53 % higher compared with methane, which is the reference fuel (4.13 kg/h vs. 3.98 kg/h for a heat input rate of 25 kW). HFO has the lowest energy saving potential, being described by a flow rate of water content in the flue gas of 2.46 kg/h for a heat input of 25 kW.

The energy saving potential by harnessing the latent heat of the water vapors in flue gas is very important for an accurate economic evaluation when several fuels are taken into account in applications based on condensing technology. In practice, the most convenient fuel – from economic point of view – is the one offering the minimum price of heat (in Euro/kWh). Hence, a certain fuel that is not the best economic option for a conventional boiler could be the most convenient solution for a condensing boiler due to a high energy saving potential by harnessing the latent heat. In other words, the energy saving potential by harnessing the latent heat may have a decisive role in establishing the most convenient fuels whether reduces significantly the heat price.

All the analyzed fuels have greater greenhouse impact than methane, which is described by $V_{CO2\ hi}$ = 0.090 Nm^3/kWh (2.25 Nm^3/h for 25 kW heat input rate). Coal gasification gas has the greatest greenhouse impact of the analyzed seven fuels, with $V_{CO2\ hi}$ = 0.199 Nm^3/kWh (4.98 Nm^3/h for 25 kW heat input rate) while propane has the lowest greenhouse impact, with $V_{CO2\ hi}$ = 0.106 Nm^3/kWh (2.65 Nm^3/h for 25 kW heat input rate).

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References

[1] H. Satyavada, S. Baldi, A Novel Modelling Approach for Condensing Boilers Based on Hybrid Dynamical Systems, Machines 4 2 (2016) p 10.

[2] D. Jones, Principals of Condensing Boiler System Design, ASHRAE Transactions 120 PT1 1 (2014).

[3] P.A. Kaczmarek, Central Heating Temperature Control Algorithm for Systems with Condensing Boilers, in: Proceedings of the 21st International Conference on Methods and Models in Automation and Robotics – MMAR 2016, Miedzyzdroje, Poland, August 29-September 01 (2016) 294-299.

[4] O.N. Zaytsev, E.A. Lapina, Increasing the Eficiency of the Condensing Boiler, in: Proceedings of the 21st International Conference "Problems of Thermal Physics and Power Engineering"– PTPPE-2017, Moscow, Russian Federation, October 9-11, 2017, IOP Conf. Series: Journal of Physics 891 (2017) 012170.

[5] L. Rosa, R. Tosato, Experimental Evaluation of Seasonal Efficiency of Condensing Boilers, Energy and Buildings 14 3 (1990) 237-241.

[6] G. Vignali, Environmental Assessment of Domestic Boilers: A comparison of Condensing and Traditional Technology Using Life Cycle Assessment Methodology, Joornal of Cleaner Production 142 4 (2017) 2493-2508.
[7] P.H. Lee, S.S. Hwang, Combustion Characteristics of Premixed Burner for Domestic Condensing Gas Boiler Using Metal Fiber and Throttle Body, Transactions of the Korean Society of Mechanical Engineers B 41 4 (2017) 249-256.
[8] M. Kovacevic, M. Lambic, L Radovanovic, J. Pekez, D. Ilic, N. Nicolic, I. Kucora, Increasing the Efficiency by Retrofitting Gas Boilers into a Condensing Heat Exchanger, Energy Sources Part B-Economics Planning and Policy 12 5 (2017) 470-479.
[9] N. Antonescu, P.D. Stănescu, Parametrical functioning study for a small boiler condensing unit, in: Proceedings of the International Conference Sustainable Solutions for Energy and Environment – EENVIRO 2016, Bucharest, Romania, October 26-28, 2016, Energy Procedia 112 (2017) 563-570.
[10] Q. Chen, K. Finney, H.N. Li, X.H. Zhang, J. Zhou, V. Sharifi, J. Swithenbank, Condensing Boiler Applications in the Process Industry, Applied Energy 89 1 (2012) 30-36.
[11] W. Chen, W. Shi, B. Wang, S. Shang, X. Li, A deep heat recovery device between flue gas and supply air of gas-fired boiler by using non-contact total heat exchanger, in: Proceedings of the 8th International Conference on Applied Energy – ICAE2016, Beijing, China, October 8-11, 2016, Energy Procedia 105 (2017) 4976-4982.
[12] X. Zhou, H. Liu, L. Fu, S. Zhang, Experimental Study of natural Gas Combustion Flue Gas Waste Heat Recovery System Based on Direct Contact Heat Transfer and Absorption Heat Pump, in: Proceedings of the ASME 2013 7th International Conference on Energy Sustainability, Minneapolis, Minnesota, USA (2013) ES2013-18316 p 8.
[13] P. Ngendakumana, F. Gabriele, Y. Restivo, K. Sartor, Energetic and Environmental Performances of a Domestic Hot Water Condensing Boiler Fired by Wood Pellets, in: Proceedings of the 11th European Conference on Industrial Furnaces and Boilers – INFUB-11, Albufeira, Portugal, April 18, 2017, Energy Procedia 120 (2017) 270-277.
[14] G. Lo Basso, B. Nastasi, D.A. Garcia, F. Cumo, How to Handle the Hydrogen Enriched Natural Gas Blends in Combustion Efficiency Measurement Procedure of Conventional and condensing boilers, Energy 123 2 (2017) 615-636.
[15] G. Kou, H. Wang, J. Zhou, S. Deng, Maximum Thermal Efficiency of Condensing Boilers Used for a Heating System, in: Proceedings of the 5h International Workshop on Energy and Environment of Residential Buildings/3rd International Conference on Built Environment and Public Health, Guilin, China, May 29-31 (2009) 2200-2203.
[16] C. Ungureanu, V. Zubcu, N. Pănoiu, I. Ionel, Combustibili, Instalaţii de ardere, Cazane, Ed. Politehnica, Timișoara, 1998 (Chapter 2) (in Romanian).
[17] Y. Zhang, M. Zhu, Z. Zhang, D. Zhang, Combustion and Emission Characteristics of a Spark Ignition Engine Fuelled with Biogas from Two-Phase Anaerobic Digestion (T-PAD), in: Proceedings of the 8th International Conference on Applied Energy – ICAE2016, Beijing, China, October 8-10, 2016, Energy Procedia 105 (2017) 137-142.
[18] J.M. Mesa-Perez, J.D. Rocha, L.A. Barbosa-Cortez, M. Penedo-Medina, C.A Luengo, E. Cascarosa, Fast oxidative pyrolysis of sugar cane straw in a fluidized bed reactor, Applied Thermal Engineering 56 (2013) 167-175.
[19] D.T. Balanescu, Generatoare de abur, Ed. Politehnium, Iași, 2014 (Chapter 2) (in Romanian).