

Possibility analysis of combustion of torrefied biomass in 140 t/h PC boiler

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Abstract. The study attempts to evaluate the impact of combustion of torrefied willow (Latin: *Salix viminalis*) and palm kernel shell (Latin: *Elaeis guineensis*) on the heat exchange in a 140 t/h PC boiler through an analysis of 6 cases for different boiler loads (60 %, 75 % and 100 %) and a comparison with coal combustion. The analysis is premised on a 0-dimensional model based on the method presented in [15, 16, 17] and long-standing experimental measurements. *Inter alia*, the following results are presented: the temperature distribution of flue gases and the working medium (water/steam) in characteristic points of the boiler as well as heat transfer coefficients for each element thereof. The temperature distribution of both fluids and the heat transfer coefficients are similar for all analysed fuels for each boiler load. However, the flue gas temperature at the outlet is higher in the case of torrefied biomass combustion. Due to that, there is an increase in the stack loss, which involves a decrease in the boiler efficiency. The conclusion is that torrefied biomass combustion is possible in a PC boiler without the need to change the boiler construction. However, it would be less effective than coal combustion.

1 Introduction

Due to the environmental policy of the European Union, there is a steady increase in the use of biomass for energy generation. The utilization of biomass in existing pulverized coal-fired (PC) boilers is related to challenges connected with its properties, such as fibrous and tenacious nature and the high moisture content [1, 2]. Compared to coal, biomass is also characterized by lower energy densities, which makes it necessary to prepare larger amounts of fuel [3]. Due to that, biomass milling and firing in already existing pulverized coal-fired systems is very difficult. Therefore, in order to make it possible, new technologies of biomass pre-treatment need to be developed.

One of such technologies is torrefaction, which is thermal processing of biomass. The process is carried out in inert atmosphere, in nearly atmospheric pressure and in temperatures usually about 200–400 °C so that volatiles, moisture and a considerable amount of acetic acid contained in biomass should be removed [4, 5]. The aim is also disintegration of lignin and cellulose contained in biomass to improve its grindability [6, 7, 8]. Thereby, biomass has a larger energy density (per a mass unit) than raw biomass and a higher lower heating value (LHV). For example, wood torrefaction causes a 30 % mass reduction (converted into gas) and only a 10 % energy reduction at the same time [9].

Torrefied biomass also contains more fixed carbon. Owing to that, it burns longer and the heating conditions in the furnace are more common to coal combustion [10].

Compared to coal, agricultural residues usually

contain more chlorine compounds, which is potentially harmful to the boiler heating surfaces due to chlorine-associated corrosion. Torrefaction reduces the chlorine content in biomass up to 50 %. Furthermore, thermal pre-treatment of biomass reduces the microbiological risk associated with the fuel transportation and storage [4].

To conclude, torrefaction makes biomass suitable for grinding in coal mills, but it is not established if biomass can substitute for coal in respect of the heat transfer in existing PC boilers.

The majority of studies on torrefied biomass combustion concern co-firing of biomass with coal or lignite. The 100 % fuel-switching issue was analysed in [11], where results of CFD modelling of torrefied palm kernel shell (PKS) combustion in a 650 t/h PC boiler were presented. Therefore, previous work has focused on the possibilities of using torrefied biomass instead of coal in existing boilers without changing the boiler construction. It reports on fundamental investigations into the combustion of torrefied PKS and willow (W) in an existing 140 t/h PC boiler through an analysis of 6 cases, for three different boiler loads (60, 75 and 100 %), and a comparison with coal (C) combustion.

PKS is residue from the African oil palm (Latin: *Elaeis guineensis*). In Poland it is considered as biomass provided it contains not more than 3 % of non-biomass contamination in the dry ash-free state [12]. Compared to other types of biomass, it is characterized by a higher LHV, a lower content of ash and a smaller amount of potassium and sodium in ash. It also contains less sulphur and chlorine than other types of agro biomass

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[13]. Owing to that, it is characterized by a low value of the fouling index (F_u), similar to values for coal, so it has a relatively low potential for causing operational problems in boilers [14].

On the other hand, owing to its availability and resistance to extreme climatic conditions, willow (Latin: *Salix viminalis*) constitutes a popular type of biomass in Poland. Its chemical composition is common to agricultural biomass such as straw or Virginia mallow - it contains more sodium, potassium, chlorine and sulphur than PKS.

The fuels under analysis (PKS and willow) were torrefied in the temperature of about 350-370 °C with a 10 minute residence time. The flue gas from the torrefaction gas combustion was used as the torrefaction medium. The torrefaction degree, defined as the ratio of volatiles released during the process to the initial volatile content of raw biomass (on the dry ash-free basis) has the following value: 32.2 % for PKS and 27.6 % for willow.

The analysis was performed by means of a 0-dimensional model based on the method described in [15, 16, 17, 18] and supported by industrial tests. In the case of thermal calculations of the furnace, the KTI method was used [15, 16, 17], while thermal calculations of the boiler convection part was based on the method presented in [18].

2 Input data

The thermal calculations are based on a 140 t/h PC boiler (Figure 1). The markings of the boiler elements and the temperatures in the boiler characteristic points shown in Figure 1 correspond to those used in the calculations.

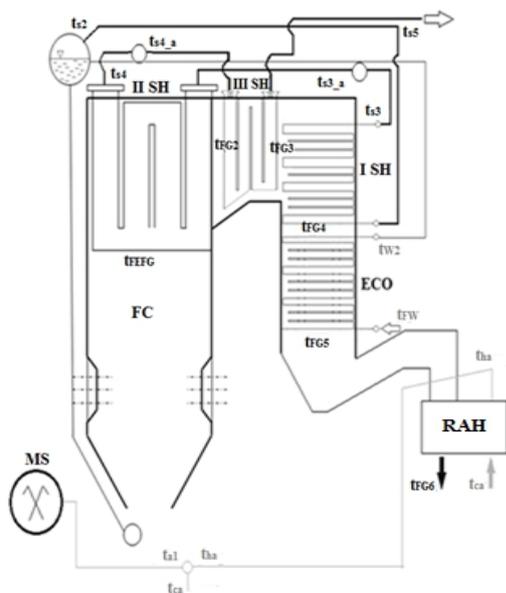


Figure 1. A schematic diagram of a 140 t/h PC boiler MS - milling system; FC - furnace; II SH - 2nd stage superheater; III SH - 3rd stage superheater; I SH - 1st stage superheater; ECO - economizer; RAH - rotary regenerative air preheater

The boiler basic operating parameters are listed in Table 1. Table 2 shows the LHV and the elemental composition of fuels.

Table 1. Basic operating parameters of the boiler

Parameter	Symbol	Value	Unit
Nominal operating capacity of the boiler	\dot{m}_s	140	t/h
Nominal temperature of live steam	t_{s_nom}	540	°C
Nominal pressure of live steam	p_{s_nom}	9.8	MPa
Temperature of feed water	t_{FW}	215	°C
Temperature of water in the attemperator	t_{W_a}	160	°C
Unburnt carbon in slag	C_s	7	%
Unburnt carbon in fly ash	C_{fa}	5	%

Table 2. LHV and elemental composition of fuels (as-received state). C - coal; PKS - palm kernel shell; W - willow

Parameter / Symbol	Value / Fuel			Unit	
	C	PKS	W		
Lower heating value	LHV	21.5	23.8	18.5	MJ/kg
Carbon content in fuel	C^{ar}	54.2	64.8	51.6	%
Oxygen content in fuel	O^{ar}	6.7	22.3	22.8	%
Hydrogen content in fuel	H^{ar}	3.4	4.3	3.7	%
Nitrogen content in fuel	N^{ar}	1.1	0.9	0.6	%
Sulphur content in fuel	S^{ar}	0.8	0.04	0.03	%
Moisture content in fuel	M^{ar}	10.3	1.1	17.7	%
Ash content in fuel	A^{ar}	23.5	6.5	3.6	%
Chlorine content in fuel	Cl^{ar}	-	0.04	0.01	%

3 Results and discussion

This study attempts to evaluate the impact of the combustion of torrefied PKS and willow on the heat transfer in a 140 t/h PC boiler through an analysis of changes in fuel and boiler load.

Three relative boiler loads were taken into consideration - 60, 75 and 100 % (of the boiler nominal load). The temperatures obtained in the boiler

characteristic points are listed in Table 3. Table 4 shows values of the stack loss, the boiler efficiency and the fuel flow rate for each case under analysis. Table 5 presents values of the heat transfer coefficient on the flue gas side in each element of the boiler.

A change in fuel involves a change in the fly ash chemical composition and, as a result, a change in the character of the heat transfer in the boiler. Biomass contains more sodium, potassium and chlorine compounds that intensify slagging and fouling of the surfaces of heat exchangers and consequently,

decrease their thermal efficiency η [19]. Due to that, it was assumed that thermal efficiency of the furnace waterwalls is reduced by 6 % in the case of torrefied biomass combustion. It was further assumed that thermal efficiency of the boiler heating surfaces is reduced by 20 % compared to coal combustion. The values are based on own unpublished research conducted by the staff of the Division of Boilers and Steam Generators of the Silesian University of Technology.

Table 3. Temperatures in the boiler characteristic points. C - coal; PKS - palm kernel shell; W - willow

Parameter / Symbol		Units	Relative boiler load								
			60 %			75 %			100 %		
			Value / Fuel								
			C	PKS	W	C	PKS	W	C	PKS	W
Furnace exit gas temperature	t_{FEFG}	°C	892	956	1025	993	1007	1074	1098	1134	1180
Flue gas temperature at the outlet of the 2 nd stage superheater	t_{FG2}	°C	663	703	783	722	743	826	806	859	931
Flue gas temperature at the outlet of the 3 rd stage superheater	t_{FG3}	°C	611	648	724	652	682	762	711	741	796
Flue gas temperature at the outlet of the 1 st stage superheater	t_{FG4}	°C	457	528	593	472	551	619	509	604	658
Flue gas temperature at the outlet of the economizer	t_{FG5}	°C	310	389	442	311	403	459	331	446	497
Exit flue gas temperature	t_{FG6}	°C	154	203	237	128	199	235	145	229	264
Temperature of feed water	t_{FW}	°C	215	215	215	215	215	215	215	215	215
Temperature of water at the outlet of the economizer	t_{w2}	°C	275	257	278	269	255	275	278	260	281
Temperature of steam at the outlet of the drum	t_{s2}	°C	310	310	310	310	310	310	310	310	310
Temperature of steam at the outlet of the 1 st stage superheater	t_{s3}	°C	389	350	378	385	349	376	405	356	381
Temperature of steam at the outlet of the attemperator downstream the 1 st stage superheater	t_{s3a}	°C	376	350	361	374	349	367	357	354	345
Temperature of steam at the outlet of the 2 nd stage superheater	t_{s4}	°C	509	476	525	502	467	523	486	486	498
Temperature of steam at the outlet of the attemperator downstream the 2 nd stage superheater	t_{s4a}	°C	509	476	504	502	467	502	485	482	453
Live steam temperature	t_{s5}	°C	540	499	540	540	492	540	540	540	540

Table 4. Stack loss, boiler efficiency and fuel flow rate. C - coal; PKS - palm kernel shell; W - willow

Parameter / Symbol		Units	Relative boiler load								
			60 %			75 %			100 %		
			Value / Fuel								
			C	PKS	W	C	PKS	W	C	PKS	W
Stack loss	S_2	%	7.3	8.12	11.9	5.9	7.9	11.8	6.8	9.3	13.4
Boiler efficiency	η	%	90.7	90.6	86.9	92.3	90.8	87.1	91.4	89.5	85.6
Fuel flow rate	\dot{B}	kg/s	2.6	2.7	3.8	3.8	3.3	4.7	5.2	4.7	6.4

Table 5. Heat transfer coefficient on the gas side in each element of the boiler. C - coal; PKS - palm kernel shell; W - willow

Parameter / Symbol		Units	Relative boiler load								
			60 %			75 %			100 %		
			Value / Fuel								
			C	PKS	W	C	PKS	W	C	PKS	W
Heat transfer coefficient on the gas side in the 2 nd stage superheater	α_{FG_IISH}	W/m ² -K	117.4	72.8	94	132.6	80.4	106.9	163.7	115.3	129.2
Heat transfer coefficient on the gas side in the 3 rd stage superheater	α_{FG_ISH}	W/m ² -K	70.4	60.8	74.5	76.8	66.7	82	182.4	171.4	195
Heat transfer coefficient on the gas side in the 1 st stage superheater	α_{FG_IISH}	W/m ² -K	63.5	42.8	53.2	68.3	47	58.5	83.5	58.8	70.5
Heat transfer coefficient on the gas side in the economizer	α_{FG_ECO}	W/m ² -K	91.1	59.5	73.4	96.2	63.9	79.3	116.7	80.3	96.5
Heat transfer coefficient on the gas side in the rotary regenerative air preheater	α_{FG_RAH}	W/m ² -K	95.5	56.8	68.5	98.1	59.5	72.2	119.7	73.3	87.4

3.1 Furnace exit gas temperature

Substitution of torrefied biomass for coal results in an increment in the furnace exit gas temperature t_{FEFG} (Figure 2). It is expressed by A.M. Gurvich's formula, which is the basis of the CKTI furnace calculation method.

$$t_{FEFG} = T_a \cdot \frac{Bo^{0,6}}{M \cdot a_{fu}^{0,6} + Bo^{0,6}}, K \quad (1)$$

T_a - adiabatic flame temperature, K,
 Bo - Boltzmann number, -,
 M - temperature field coefficient, -,
 a_{fu} - furnace emissivity, -.

Temperature field coefficient M depends on the relative level of burners in the boiler, the fuel properties, such as the state and the volatile fraction content, and the furnace type. None of these parameters change for PKS, willow or coal, so coefficient M could be considered as constant.

However, other parameters change due to the fuel replacement (Figure 3). Adiabatic flame temperature T_a depends on the amount of heat released from fired fuel and heat introduced into the furnace by air [17]. Mostly it depends on heat released from fuel, i.e. there is a direct dependence on the fuel LHV. Compared to coal or willow, PKS is characterized by a higher LHV, so in this case T_a has the highest values.

Boltzmann number Bo value is proportional to the fuel flow rate. Therefore, willow has the lowest

LHV of the fuels under analysis, and it has the highest values of the fuel flow rate and, consequently, of the Boltzmann number.

Furnace emissivity a_{fu} depends on flame emissivity a_{fl} . Flame emissivity depends directly on the flue gas composition, specifically - on the contents of fly ash, moisture and triatomic gases. The fly ash content has a dominant influence on a_{fl} , because of its better radiative properties compared to other components. Torrefied biomass contains less ash than coal (by about 17-20 %). For this reason, flue gases contain less fly ash, deteriorating the radiative properties. Due to that, a smaller amount of heat is absorbed by the furnace waterwalls, and, in consequence, more heat remains in flue gases.

The flue gas temperature at the furnace outlet is affected by any change in the parameters under consideration, but it is the Boltzmann number that has the greatest effect. According to it, t_{FEFG} increases by an average of 20 °C for PKS and 66 °C for willow combustion compared to coal combustion.

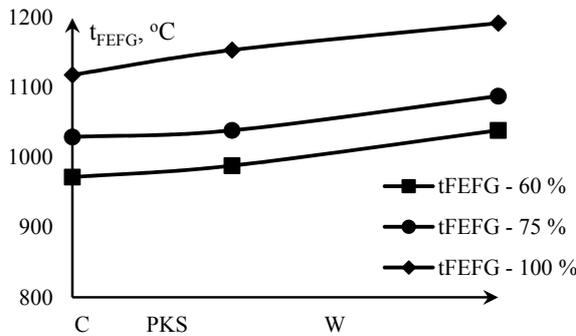


Figure 2 Furnace exit gas temperature as a function of the fuel type and the boiler relative load (60, 75 and 100 %)

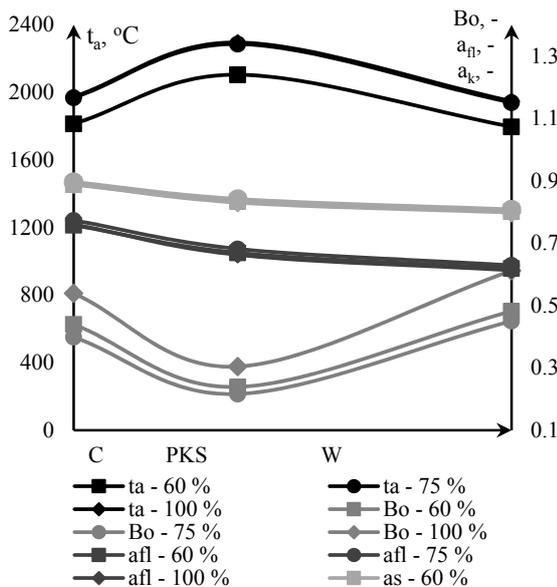


Figure 3 Adiabatic flame temperature, Boltzmann number, flame emissivity and furnace emissivity as a function of the fuel type and the boiler relative load (60, 75 and 100 %)

3.2 Flue gas and water/steam temperatures in the boiler

An increase of furnace exit gas temperature in the case of torrefied biomass combustion results in a rise in other temperatures in the boiler characteristic points. Nevertheless, the nature of the flue gas temperature distribution is similar for each fuel combustion. Due to that, it could be considered that PKS, willow and coal are characterized by similar parameters of the heat exchange, therefore torrefied biomass has the potential to substitute for coal in existing PC boilers.

Figures 4, 5 and 6 show the temperature distribution in the boiler for each relative load and fuel type.

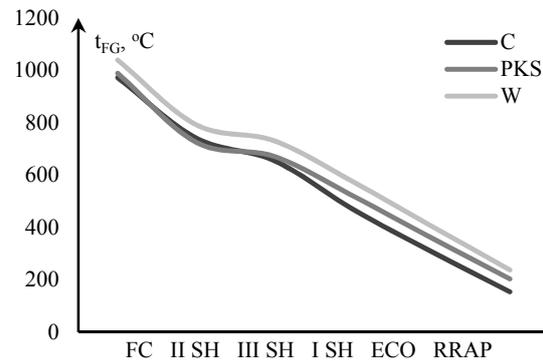


Figure 4. Flue gas temperature distribution in the boiler characteristic points for the boiler relative load of 60 %

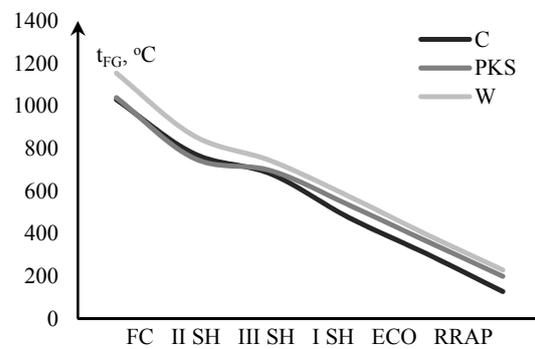


Figure 5. Flue gas temperature distribution in the boiler characteristic points for the boiler relative load of 75 %

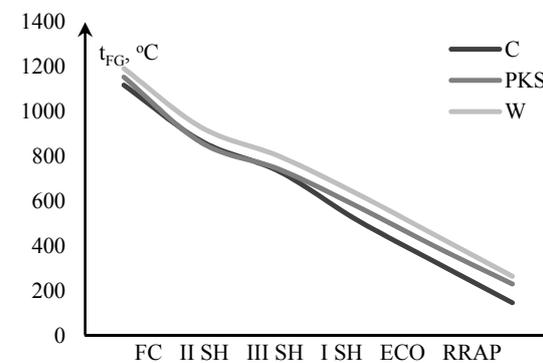


Figure 6. Flue gas temperature distribution in the boiler characteristic points for the boiler relative load of 100 %

There are some differences between the analysed fuels in the case of the working fluid (water/steam) temperature distribution in the boiler. The temperature distribution nature is still similar, but in the case of PKS combustion, the nominal exit steam temperature (540 °C) is not maintained for the boiler relative load included in the range of 60 to 75 % (Figures 7, 8 and 9). This is caused by the PKS high LHV, which results in the low fuel flow rate. Due to that, the amount of flue gases is much lower compared to coal or willow combustion, and this means the flue gas lower velocities. Considering also reduced thermal efficiency of the boiler heating surfaces, the heat transfer is significantly worse in the case of PKS combustion. It might be concluded that in such a case it will be necessary to enlarge the boiler heating surfaces, which would involve the need to change the boiler construction.

However, most types of palm kernel shell are characterized by lower LHV's than the one analysed herein (23.8 MJ/kg) – the values are usually about 19-21 MJ/kg (depending on the temperature of torrefaction) [20, 21], whereas the PKS higher heating value (HHV) is usually about 22.9 MJ/kg [22]. In such a case, the live steam temperature is maintained.

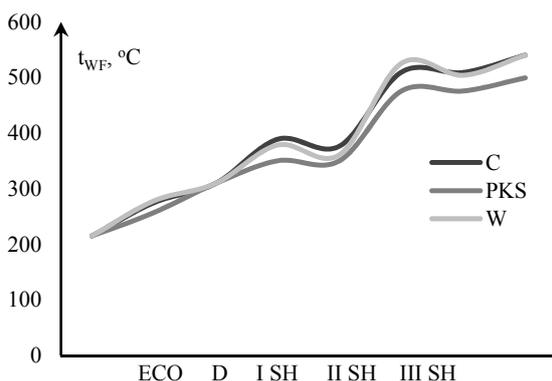


Figure 7. The working fluid temperature distribution in the boiler characteristic points for the boiler relative load of 60 %

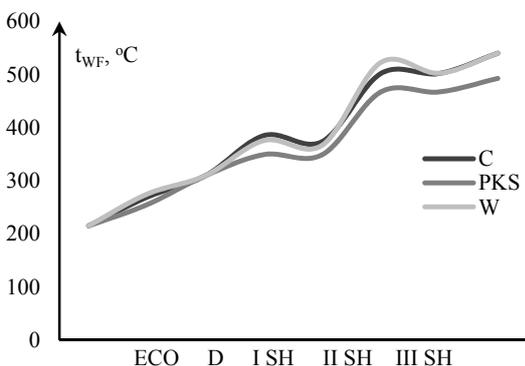


Figure 8. The working fluid temperature distribution in the boiler characteristic points for the boiler relative load of 75 %

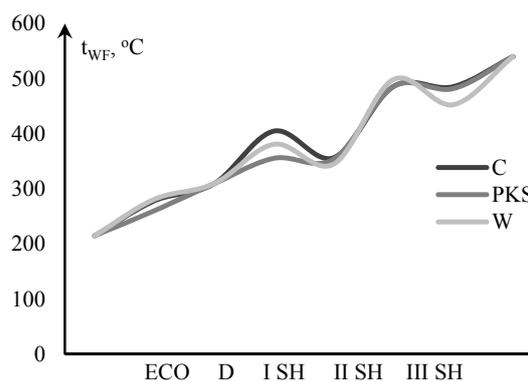


Figure 9. The working fluid temperature distribution in the boiler characteristic points for the boiler relative load of 100 %

3.3 Boiler efficiency

An increase in the furnace exit gas temperature and a reduction in thermal efficiency of the boiler heating surfaces involve a rise in the exit flue gas temperature. This results in an increase in the stack loss (Figure 10) and, in consequence, a decrease in the boiler efficiency which is reduced on average by 1.2 percentage points (pp) for PKS and by about 5 pp for willow combustion compared to coal combustion (Figure 11).

However, taking account of environmental and economic benefits of biomass combustion, these values are not significant enough to discredit it. In this case, consideration should be given to the use of such waste heat, as an additional benefit of the fuel replacement.

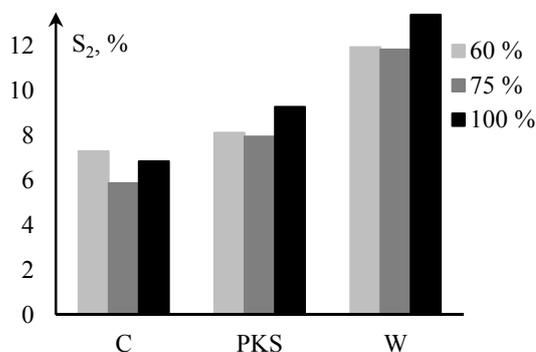


Figure 10. Stack loss as a function of the fuel type and the boiler relative load (60, 75 and 100 %)

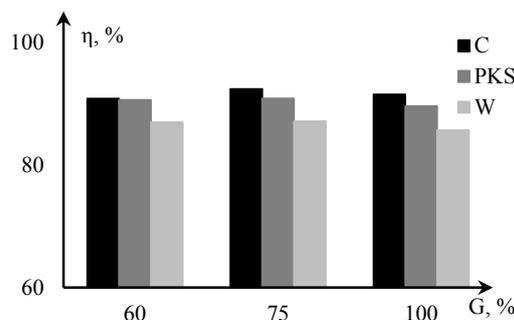


Figure 11. Boiler efficiency as a function of the boiler relative load (G) and the fuel type

3.4 Flue gas heat transfer coefficient

According to the similar temperature distributions of the fluids, the nature of the heat exchange in the boiler elements should be similar for each fuel type. It is well demonstrated by the overall heat transfer coefficient k . Figures 12 and 13 show it on the example of the 2nd and the 1st stage superheater. These components were chosen because of the difference between the kind of the heat exchange – the 2nd stage superheater is classified as the radiant and the 1st stage superheater as the convective type of a heat exchanger.

Otherwise, the heat transfer coefficient on the gas side α_{FG} changes slightly according to changes in fuel (Figures 14 and 15). Despite an increase in the mean temperature difference in all heat exchangers of the boiler, the values of α_{FG} are reduced in the case of torrefied biomass combustion. It is particularly noticeable in the case of the 2nd stage superheater. This is due to the deterioration in the flue gas radiative properties and, in consequence, in the gas emissivity. It also results from a reduction in the flue gas velocity, which deteriorates the convective heat exchange. It is mostly the effect of the change in the flue gas temperature and density.

Due to lower live steam temperatures in the case of PKS combustion, the values of α_{FG} are in fact lower for that type of torrefied biomass. If PKS has a lower LHV, its values of α_{FG} would be close to values for willow.

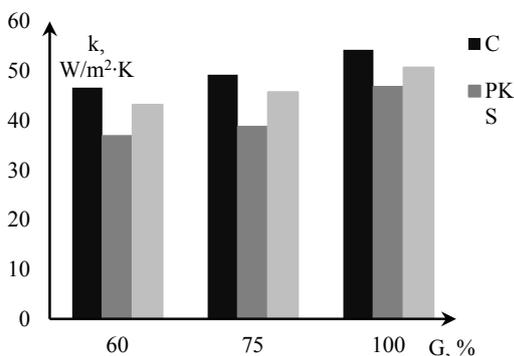


Figure 12. Overall heat transfer coefficient in the 2nd stage superheater as a function of the boiler relative load (G) and the fuel type

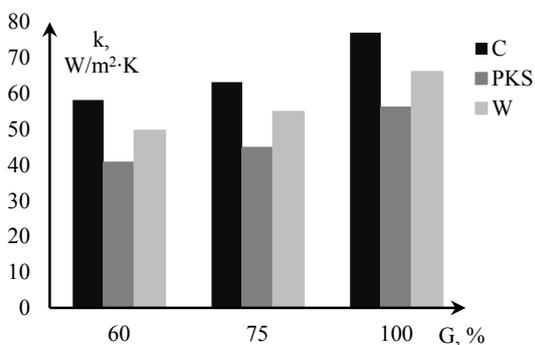


Figure 13. Overall heat transfer coefficient in the 1st stage superheater as a function of the boiler relative load (G) and the fuel type

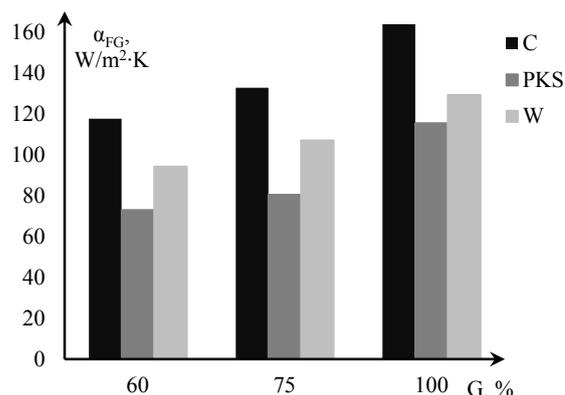


Figure 14. Heat transfer coefficient on the gas side in the 2nd stage superheater as a function of the boiler relative load (G) and the fuel type

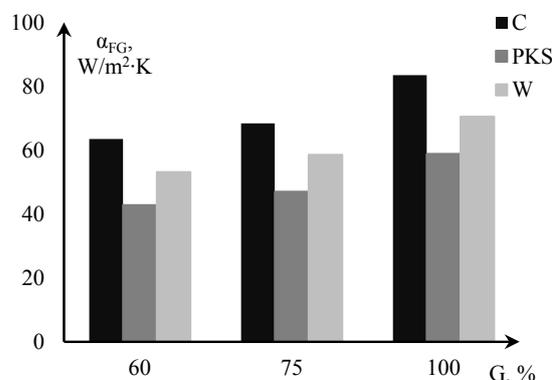


Figure 15. Heat transfer coefficient on the gas side in the 1st stage superheater as a function of the boiler relative load (G) and the fuel type

4 Conclusion

The possibility of substituting torrefied biomass for coal depends on the biomass type, especially on its elemental composition and the LHV. As most types of agro biomass are similar to willow, it might be assumed that most of them could be used instead of coal in existing PC boilers.

In the case of PKS combustion, live steam temperatures for the boiler relative load of 60 and 75 % are not maintained as a result of the fuel high LHV. However, most torrefied palm kernel shells have lower LHV's compared to the type analysed herein, so it could be assumed that in most cases of PKS combustion the temperatures would be equal to the nominal value.

Combustion of torrefied biomass in a PC boiler causes an increase in the furnace exit gas temperature and a decrease in thermal efficiency of the heating surfaces. In consequence, there is a rise in the exit flue gas temperature, which causes a reduction in the boiler efficiency by about 1.2 pp for PKS and by 5 pp for willow combustion. A further analysis is required to establish whether this would be compensated for by the benefits of biomass combustion.

In addition, it should be noted that PKS shipment from distant regions of the world requires energy derived from fossil fuels. In view of the increasing number of power plants firing imported biomass, this issue has raised concern and become the subject of analyses. It is estimated that emissions from the transport of such biomass constitutes about 15% of total avoided emissions compared to coal combustion [23]. Besides, as mentioned in [24], a reduction in savings of emissions from biomass combustion could reach 15-50 % due to its importation and to using nitrogen fertilisers. Therefore, the regulations concerning classification of PKS and other imported biomass types as a 100% renewable energy source should be corrected by appropriate legislation.

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References

1. V. Repellin, A. Govin, M. Rolland, R. Guyonnet, *Biomass Bioenerg.* **23**, 923-930 (2010)
2. B. Arias, C. Pevida, J. Feroso, M.G. Plaza, F. Rubiera, J.J. Pis, *Fuel Process. Technol.* **89**, 169-175 (2008)
3. T. G. Bridgeman, J. M. Jones, I. Shield, P.T. Williams, *Fuel* **87**, 844-856 (2008)
4. M. Kopczyński, J. Zuwała, *Biomass torrefaction as a way of elimination of technical barriers existing in large-scale co-combustion* (Polityka Energetyczna, Kraków, 2013) [in Polish]
5. M. Kratofil, R. Zarzycki, R. Kobylecki, Z. Bis, *Investigation of biomass torrefaction process* (Zeszyty naukowe Politechniki Rzeszowskiej 291, Rzeszów, 2015) [in Polish]
6. D. T. Van Essendelft, X. Zhou, B.S.-J. Kang, *Fuel* **105**, 103-111 (2013)
7. M. Phanphanich, S. Mani, *Bioresour. Technol.* **102** 1246-1253 (2011)
8. L. Kokko, H. Tolvanem, K. Hamalainen, R. Raiko, *Biomass Bioenerg.* **42**, 219-223 (2012)
9. M. J. C. van der Stelt, H. Gerhauser, J. H. A. Kiel, K. J. Ptasiński, *Biomass Bioenerg.* **35**, 3748-3762 (2011)
10. B. Batidzirai, A. P. R. Mignot, W. B. Schakel, H.M. Junginger, A. P. C. Faaij, *Energy*, **62**, 1-19 (2013)
11. J. Li, A. Brzdekiewicz, W. Yang, W. Blasiak, *Appl. Energ.* **99**, 344-354 (2012)
12. Energy Regulatory Office, *Appendix 1 to Communication 30/2011 on biomass classification for energy purposes* (Warszawa, 2011) [in Polish]
13. B. Jagustyn, I. Patyna, A. Skawińska, *Chemik* **67**, 6, 552-559 (2013)
14. R. Rajczyk, *Magazyn Biomasa*, **4**, 9-14 (2015)
15. P. Orłowski, W. Dobrzański, E. Szwarz, *Steam boilers* (WNT, Warszawa, 1979) [in Polish]
16. *Teplowej rasczet kotelnych agregatov (Normativnyj metod)* (Energia, Moskwa, 1973) [in Russian]
17. P. Basu, C. Kefa, L. Jestin, *Boilers and Burners Design and Theory* (Springer, New York, 2000)
18. M. Pronobis, *Heat transfer in contaminated convection boiler surfaces* (Zeszyty Naukowe Politechniki Śląskiej seria: Energetyka, Gliwice, 1992) [in Polish]
19. M. Pronobis, W. Wojnar, *Energ. Convers. Manage.* **74**, 461-470 (2013)
20. A. A. Jaafar, M. M. Ahmad, *Int. J. Chem. Mol. Nucl. Mater. Metall. E.* **12**, 1106-1109 (2011)
21. H. Pawlak-Kruczek, M. Czerep, *Nowa Energia* **1**, 31-38 (2016)
22. W. Kordylewski, A. Tatarek, *Archiwum Spalania* **12**, 3, 109-116 (2012)
23. A. Adamkiewicz, W. Zeńczak, *Rynek Energii* **6**, (2015)
24. S. Korhaliller: *The UK's Biomass Energy Development Path* (International Institute for Environment and Development, London, 2010)