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COMBUSTION OF PITCOAL-WOOD BIOMASS BRICHETTES IN A BOILER TEST FACILITY

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Abstract

The use of composite fuels using pitcoal and sawdust represents a high perspective. The paper deals with the experimental results focusing on the combustion efficiency of composite fuel briquettes and on the polluting emissions level. A special care is given to the determination of boiler efficiency and to the establishment of exploiting economic conditions, like the supply, cleaning etc. The research of the combustion of pitcoal-wood biomass briquettes is conducted on a 55 kW boiler. A numerical modeling of the combustion processes within the boiler allowed a critical comparison between the experimental and numerical data.

Key words: composite fuel briquettes, combustion, numerical modelling, emission reduction

1. Introduction

The research of the combustion of pitcoal-wood biomass briquettes is conducted on a 55 kW boiler (Azapagic 2007). A boiler with reduced thermal power, which can supply a residential area of 500 m^2 or a small commercial area, was chosen.

The concept to implement the use of composite fuels in hill and mountain forestry area was the principle of the research, (Axinte et Al. 2003; Prisecaru et al. 2007; Pănoiu et al. 2008). Fig. 1 shows the boiler test facility, built by PIFATI SA, present in the Laboratory of Boilers and Combustion Installations of the Department of Classic Thermo-mechanic and Nuclear Equipment, University Politehnica of Bucharest. The boiler has a cast iron grid for combustion, with a small slope towards the supply door.

The experimental researches are focusing on the combustion efficiency of composite fuel briquettes and on the polluting emissions level (Grant 2006). A special care is given to the determination of boiler efficiency and to the establishment of exploiting economic conditions, like the supply, cleaning etc. The boiler characteristics are presented in Table 1, (Pănoiu et al., 2008).

2. Characteristics of the 55 kW boiler

The 55 kW test facility boiler has the following dimensions of the furnace:

Depth: L_f=750 mm;
Width: l_f = 550 mm;
Height: h_f = 600 mm;
Volume: V_f = 0.25 m^3.

The furnace is equipped with a grid with fixed bars, having the dimensions (Fig. 2):

Length: L_g = 520 mm;
Width: l_g = 550 mm;
Bars width: l_b = 15 mm;
Bars spacing: s = 15 mm;
Length of the free space between bars l_{sl} = 360 mm;
Grid surface S_g = 0.286 m^2;
Grid active surface S_{ga} = 0.19 m^2.

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Table 1. Boiler characteristics

Boiler	**Power**[*]		**Pressure**	**Sizes**							
	Kcal/h	kW	p_{max} bar	A mm	A_1 mm	B mm	B_1 mm	E mm	E_1 mm	H mm	C mm
	50000	58	3	810	880	660	740	1590	1720	1116	1250

[*] for this boiler type a 78% efficiency is considered

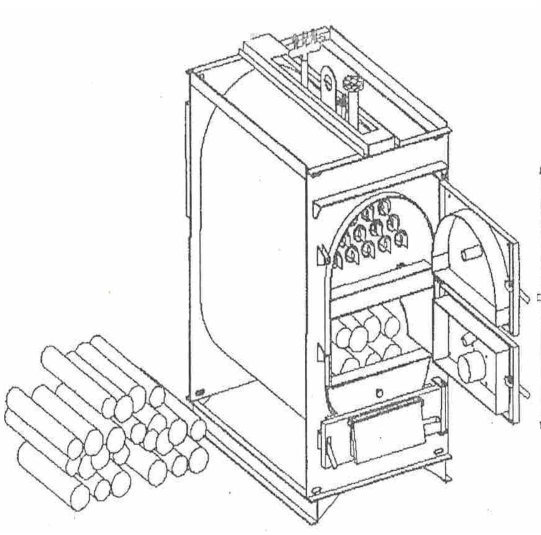

Fig. 1. 55 kW boiler

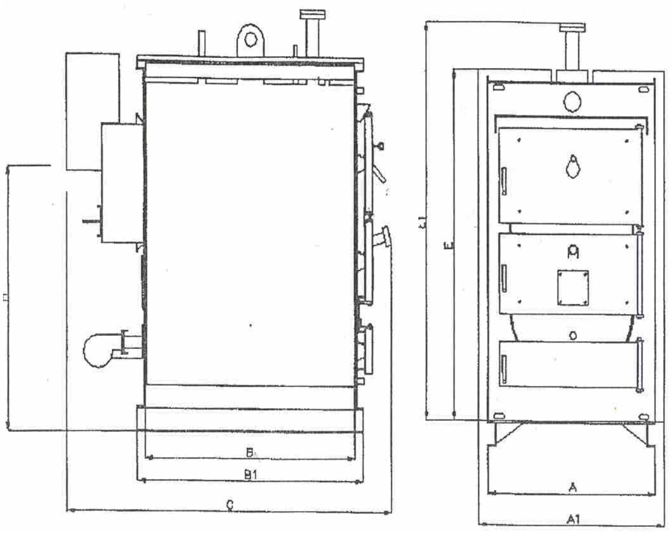

Fig. 2. The actual size of the boiler

The fuel flow necessary to achieve 55 kW thermal power (P_t) is given by Eq. (1):

$$B\left[\frac{kg}{s}\right]=\frac{P_t}{Q_i^i\cdot\eta} \tag{1}$$

where: Q_i^i [kJ/kg] is the fuel low heat value.

For briquettes composed from pitcoal from Romanian Jiu Valley and wood wastes like sawdust, the low heat value varies between 12500 kJ/kg and 13200 kJ/kg, (Lăzăroiu et al., 2008). Elemental composition of the components and composite from the briquette is presented in Table 2.

Table 2. Elemental composition of the components and composite from the briquette

Element	*Symbol*	*U.M*	*Biomass and molasses*	*Pitcoal*	*Composite*
Carbon	C^i	%	46.48	21.20	28.23
Hydrogen	H^i	%	6.10	1.40	2.74
Oxygen	O^i	%	41.80	2.52	14.49
Azoth	N^i	%	0.63	0.14	0.28
Sulfur	S^i_c	%	0.00	0.40	0.26
Ash	A^i	%	1.17	70.52	50.18
Total	W^i_t	%	3.82	3.82	3.82

Considering a low heat value of 12,700 kJ/kg, the rate of the fuel flow is:

$$B=\frac{55}{12700\cdot 0.7}=0,006 \quad [kg/s]=22.2\,[kg/h] \tag{2}$$

Using this value, the operational coefficients for the boiler are:

- total gravimetric load of the grid:

$$q_{gr}=\frac{0.006}{0.286}=0.021 \quad [kg/m^2\cdot s] \tag{3}$$

- gravimetric load of the combustion area:

$$q^*_{gr}=\frac{0.006}{0.19}=0.031 \quad [kg/m^2\cdot s] \tag{4}$$

- total specific thermal load of the grid:

$$q_{gr}=\frac{0.006\cdot 12700}{0.286}=269\,[kg/m^2\cdot s]$$

o (5)

- specific thermal load of the grid active area:

$$q_{gr}=\frac{6\cdot 12700}{190}=400\,[kg/m^2\cdot s] \tag{6}$$

- active section of the grid: 0.346; cooling index of the grid bars: 1.33;

- thermal load of the furnace width:

$$q_l = \frac{B \cdot Q_i^i}{l_f} = \frac{0.6 \cdot 12700}{55} = 140\ [kW/m] \quad (7)$$

- thermal load of the grid bars width:

$$q_l^* = \frac{B \cdot Q_i^i}{l_f} = \frac{6 \cdot 12700}{275} = 280\ [kW/m] \quad (8)$$

- thermal load of the furnace volume:

$$q_v = \frac{B \cdot Q_i^i}{V_f} = \frac{6 \cdot 12700}{250} = 305\ \left[kW/m^3\right] \quad (9)$$

3. Experimental results

The experimental data are presented in Table 3 and Table 4.

The taste data values for the 50 kW load have indicated:

- a quantity of slag evacuated below the grid of 5.5-6.5%; the volume of the slag retaining room of 0.5x 0.54 x 0.6 = 0.162 m^3 allows an evacuation at 6 hours;
- the disturbance of the mixture layer pitcoal-sawdust is occurring at a period of 2-3 hours;
- the temperature of the fuel layer during the combustion was of 850ºC;
- the temperature of the stack flue gas was below 160ºC;
- the air excess of the stack flue gas had optimal values for the combustion technology in fixed layer below 3.5;
- the measured efficiency is over 76%;
- the pollutants emissions are reduced. If a reference air excess characterized by an oxygen percentage in the exhausted gases of 11% is considered, the CO emissions are below 500 mg/m^3, NO$_x$ emissions below 185 mg/m^3 and SO$_2$ emissions below 300 mg/m^{3}N.

The performances of the nominal operation load were kept both for 45 kW (90%) ad 40 kW (80%) loads. For a boiler load below 60%, a reduction with 4-5% of the efficiency was observed.

The thermal power was determined by measuring the heated water flow in the boiler and the difference of the boiler outlet and inlet water temperatures.

Flame aspect after 1.5 hours from fuel feeding is shown in Fig. 3 and the smoke aspect at the stack evacuation is shown in Fig. 4.

Thermal power is expressed by Eq. (10):

$$P_t = 4.18 \cdot D_a \cdot (t_e - t_i)\ \text{[KW]} \quad (10)$$

where:

D_a – water flow, kg/s;

t_e – outlet temperature of the boiler water, ºC;

t_i – inlet temperature of the boiler water, ºC.

Table 3. Experimental data sheet no. 1

No.	***Operating characteristic***	***U.M.***	***Measurement***			
			1	***2***	***3***	***4***
1	Thermal load	kW	50	50	50	49
2	Combustible flow	kg/h	17	16.9	17	17
3	Slag	kg/h	0.88	0.9	0.9	0.89
4	Ash	kg/h	2.8	2.75	2.8	2.75
5	Stack temperature (t_{ev})	^{0}C	160	161	160	162
6	Water flow (Da)	kg/h	810	812	811	812
7	Inlet water temperature (t_i)	^{0}C	8	8	8	8
8	Exit water temperature (t_e)	^{0}C	59	61	61	61
9	CO$_2$ emission	%	3,9	4.0	3.8	3.9
10	SO$_2$ emission	ppm	70	72	72	70
11	NO emission	ppm	30	30	27	26
12	NO$_2$ emission	ppm	0	10	0	0
13	NOx total emission (NO+NO$_2$)	ppm	30	40	27	26
14	CO emission	%	0.24	0.16	0.2	0.18
15	Furnace air excess, λ_f		3.2	3.1	3.2	3.3
16	Stack air excess, λ co		3.4	3.4	3.37	3.4
17	Oxygen in the stack exhaust gases (O$_2$)	%	14.8	14.6	14.6	14.7
18	Air temperature	^{0}C	15	17	16.5	17
19	Average ambient temperature	^{0}C	2	2	2	2
20	Indirect efficiency		76.7	77.1	77.2	78.1

Table 4. Experimental data sheet no. 2

No.	***Operating characteristic***	***U.M.***	***Measurement***			
			1	***2***	***3***	***4***
1	Thermal load	kW	45	44.9	45	45
2	Combustible flow	kg/h	15.2	15.2	15.2	14.9
3	Slag	kg/h	0.86	0.86	0.88	0.9
4	Ash	kg/h	2.60	2.61	2,60	2.61
5	Stack temperature (t_{ev})	^{0}C	159	157	157	157
6	Water flow (Da)	kg/h	730	726	769	728
7	Inlet water temperature (t_i)	^{0}C	8	8	8	8
8	Exit water temperature (t_e)	^{0}C	61	59	60	60.5
9	CO_2 emission	%	3.9	3.89	3.9	3.91
10	SO_2 emission	ppm	71	72	68	72
11	NO emission	ppm	30	32	31	32
12	NO_2 emission	ppm	14	15	18	17
13	NOx total emission ($NO+NO_2$)	ppm	44	47	49	49
14	CO emission	%	0.16	0.16	0.13	0.14
15	Furnace air excess, λ_f		3.3	3.55	3.3	3.3
16	Stack air excess, λ co		3.5	3.55	3.5	3.49
17	Oxygen in the stack exhaust gases	%	14.9	14.9	14.79	14.9
18	Air temperature	^{0}C	14	15	15	15
19	Average ambient temperature	^{0}C	-2	-2	-2	-2
20	Indirect efficiency		76.5	76.5	76.6	76.6

Fig. 3. Flame aspect

The air flow was controlled through the valve on the inferior side of the boiler combustion chamber, the air being conducted further to the grid and the briquettes layer. At the same time, the air admission was controlled according to the stack depression (by aid of a control valve placed at the boiler end). After the load settlement, the air and the depression are established such as the pollutant emissions to be as low as possible (CO, NO_x) and the temperature of the stack exhausted gases as low as possible; in these conditions the air excess was between 3 and 4.5. The fuel disturbance was made once every 2-4 hours, and the slag evacuation once every 4-6 hours.

Representative samples of flow slag and ash were collected and tasted in laboratory boiler.

As results were obtained: C_{zg} = 18%; C_{an} =5% (combustible material in slag and ash); a_{zg} = 0.06; a_{an} = 1 – 0.06 = 0.94 (retaining degree under the shape of slag and ash).

Fig. 4. Monitoring the smoke aspect at the stack

After computation, the values for the percentage heat losses are: loss through incomplete combustion from the mechanical point of view, q_m = 2.46; loss through incomplete combustion from the chemical point of view, q_{ch} = 3.57; loss through the enthalpy of the residuum evacuated from the furnace, q_{rf} = 0.056 %.

For a temperature of the stack exhausted gases of 160ºC and an air excess λ_{ev} = 3.4, the heat percentage loss at evacuation resulted q_{ev} = 29.3%. For computing the heat losses through incomplete chemical combustion, the CO emission had the average value of 0.18%, and the volume of the dry exhausted gases of V_{gu} = 22.56 m^3_N/kg.

On a statistical basis, the heat loss towards the ambient is determined q_{ex} = 1.5. Using the percentage heat losses, the installation efficiency is:

$$\eta = 100 - \left(2.46 + 3.57 + 15 + 0.056 + 29.3\right) = 63.12\% \tag{11}$$

The difference between the efficiency computed with the gas analyzer and Eq. (11) is given by the fact that the gas analyzer does not consider the loss q_{ev}.

The sum of the losses not considered by the gas analyzer is:

$$q_m + q_{ch} + q_{rf} + q_{ex} = 7.58\% \tag{12}$$

The efficiency computed only using the heat percentage losses at the stack exhausted gas will be:

$$\eta = 100 - 29.3 = 70.7 \tag{13}$$

The efficiency measured with the gas analyzer was $\eta = 77.2$. The percentage error is

$$\Delta\eta = \frac{77.2 - 70.7}{77.2} \cdot 100 = 8.41\% \tag{14}$$

The combustion technology on fix grid, with manual distribution of the fuel layer, experimented on the 55 kW test boiler allow obtaining good results for the mixture pitcoal-sawdust combustion. Thus, the efficiency was within admissible limits and the pollutant emissions well below the regulated threshold of 400 mg/m^3_N, both for NOx as well as for SO_x (for CO does not exist yet a regulated threshold), (Lăzăroiu, 2007).

The experimental results were compared with the ones obtained through numerical simulation using the software FLUENT. The numerical modeling allowed the determination of the heat field within the furnace, on the grid and within the smoke pipes. These data allow also estimating the installation reliability and the efficiency value (Gavrilescu 2002).

4. Numerical modeling results

For geometric modeling of the 55 kW experimental boiler, 164483 cells were used, grouped as: 147538 cells with tetrahedron form; 16945 cells with hexagon form. For the turbulence model, the Spalart-Almaras model was used. This model is specific for the reduced turbulences (the combustion of the mixture combustible particles on the grid in a fixed layer conducts to a reduced turbulence). For the radiation model, the “6 fluxes model” was used.

For the radiation model, the physical measures imposed are: average absorption, ε_p = 0.35 m^{-1}; average particles spreading coefficient, 0; metallic wall emission factor ε = 0.8, (Mihăescu et al., 2007). For the coke particles drawn in suspension by the combustion gases the size of $4.38 \cdot 10^{-4}$ m was chosen.

For simulating the composite combustible granulation the real size of the briquettes with diameter of 40 mm and height of 40 mm was used.

The results highlighted that the combustion area of the furnace is sufficiently large to ensure a good combustion. Thus, the CO emission on the furnace end was 0.03 kg/kg. For an oxygen concentration of approximately 7% within the combustion gases, the corrected emission of CO at the flame ending was CO = 970 mg/m^3_N.

The average temperature at the middle of the furnace was 1092ºC. This value is very high for the combustion technology on the grid with fixed layer. In practice, high values of the air excess and temperatures at the furnace end within 850-900ºC are adopted.

The numerical modeling result, through combustion performances, indicates as future perspective the possibility to reduce the air excess and to increase the layer and flame temperature. It must be mentioned that this boiler has cast iron grid and thus the operation with high temperatures within the combustion area are allowed. Fig. 5 shows the field of the thermal flux in W/m^2 for the area at the boiler top.

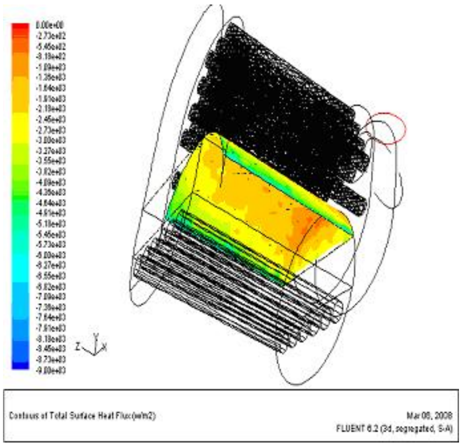

Fig. 5. Heat flux on the furnace top

The thermal flux at the flame end represents the result of the radiation process, the respective heat being taken by the first row of smoke pipes placed towards the furnace. The thermal flux received by the grid bars is shown in Fig. 6. This flux has values between 20 and 40 W/m^2. The air cooling of the bars allows their good operation. Fig. 7 illustrates the thermal flux distribution on the smoke pipes wall. The temperature variation from the furnace area is illustrated in Fig. 8.

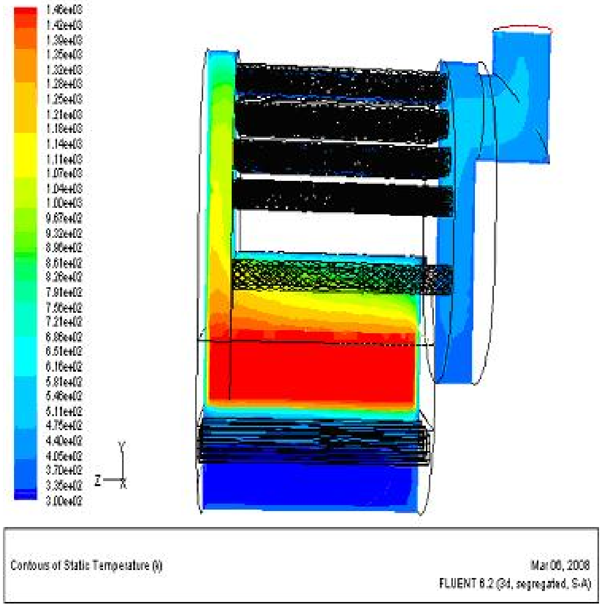

Fig. 6. Temperature field for the furnace

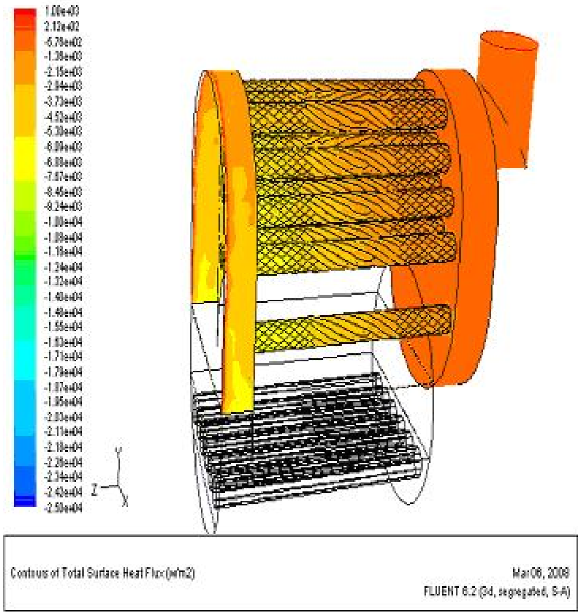

Fig. 7. Heat flux distribution on the smoke pipe walls

The resulted values during the combustion process are between the normal limits for the calorific power of the combustible mixture. It must be noted the efficient cooling of the grid bars, resulting a possibility for their long exploitation.

5. Conclusions

The numerical modeling data of the complex processes within the furnace, containing combustion reactions, heat emitting, heat exchange through radiation and partially convection, flow and pollutant emissions, can be used for the design of new installations or for instructions for an economic exploitation of these type of installations.

The validation of the numerical computation model applied to the experimental boiler can be considered realized through the value of the exhausted gases temperature at stack outlet, around 300ºC and through the CO emission, having values approximately equal with the ones experimentally determined.

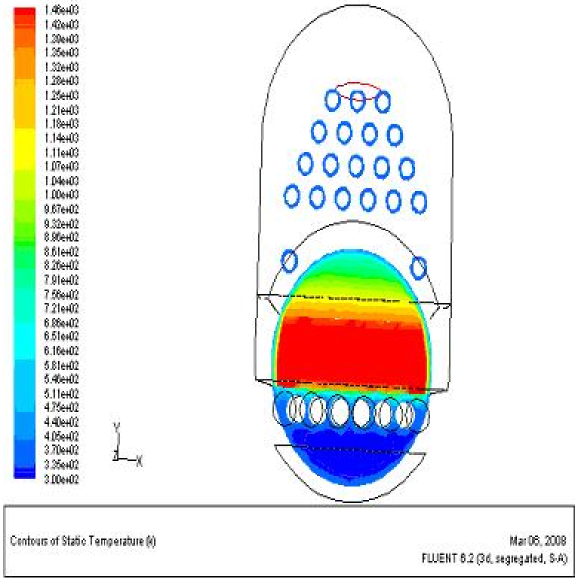

Fig. 8. Temperatures distribution for the furnace area

The numerical values obtained through the mathematical modeling of the thermal transfer process through radiation with applicability for the 55 kW experimental boiler brought new data with respect to the ones experimentally obtained. The values of the thermal flux on the furnace areas must be mentioned.

The data obtained through mathematical modeling highlighted a good cooling of the grid bars (leading to a high durability of these) and relatively low temperatures for the furnace main area.

The rate distribution highlighted a uniform distributed combustion that leads to a high efficiency. The temperatures from the furnace area within the combustion technology on the grid are very difficult measured. The most efficient method is using infrared pyrometers, but the area visible area is very reduced, such that the data obtained thorough numerical modeling represents an unique and of high value information. The same thing can be told on the rate field.

The use of composite combustibles using pitcoal and sawdust represents a certain perspective. Thus, the calorific power is high for obtaining feasible loads of the combustion space leading to corresponding efficiencies and to the enlargement of the period between two refuels. Due to the relatively sterile contain from the composite combustible, the slag quantity that must be evacuated sensible is reducing. The pollutants emissions are at the normal limits for the grid combustion technology.

The good results obtained at the combustion on fixed grids of the composite combustible recommends the enlargement of the combustion researches also on mobile grids, thing that leads to the increase of the thermal power for these boilers.

Acknowledgments

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