ENERGY EFFICIENCY ANALYSIS OF A BIOMASS SYSTEM THROUGH MONITORING OF RELEVANT PARAMETERS

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Abstract - This paper is based on a study dedicated to the overall energy balance (EB) of a biomass system, particularly focusing on a prototype design for commercial use. The EB was developed in accordance with the guidelines outlined by the Romanian Agency for Energy Conservation (ARCE), No. 245. Through the measurements conducted and calculations performed, we established the EB (EB), which allowed the identification of energy losses and will help to increase the system efficiency in the future. A monitoring system was created by the authors of this paper and was used for real-time tracking and display, respectively storage of operational parameters. The mathematical model for the EB of the analyzed commercial prototype will also be presented. Multiple operational regimes, characterized by varying thermal power values, were considered in the EB. The experimental results were entered and calculated with the presented mathematical model and the obtained results are presented in the conclusions.

Keywords: biomass utilization, EB, efficiency of biomass heating system, prototype monitoring, experimental measurements analysis.

Abbreviations: ARCE - Romanian Agency for Energy Conservation; EB - Energy Balance; CC - Combustion Chamber.

1. INTRODUCTION

The growth of renewable energy and improvements in energy efficiency are essential. Biomass plays a pivotal role in achieving the Green Deal objective of reaching climate neutrality by 2050. An essential biomass technology is the combustion of pellets in household pellet boilers [1,2]. This stands out as the most efficient and environmentally friendly method of utilizing biomass for residential heating [3,4].

Biomass plays a significant role in the EU, as indicated by the regulations and policies introduced in recent years [5,6], as well as the evolution of the shares in biomass utilization over the past years, as highlighted in several studies in the field such as [1,2,3,4].

Within the framework of a comprehensive investigation focused on the monitoring and assessment of a prototype system (Figure 1) for thermal energy production using biomass as fuel.

With the main objective of optimization based on obtained results, this scientific paper present two scenarios of different operating modes for which EB were conducted, and energy losses were identified. In these cases, the results of the measurements conducted on the analyzed system ultimately led to the formulation of conclusions and actions aimed at improving the efficiency of the analyzed system.

Several monitoring series were carried out, among which, in this paper, we present two cases, further referred as Case 1 and Case 2.

Assessing the composition of flue gases is essential for ensuring an efficient and environmentally friendly operation of the entire system. For this purpose, we have used gas analyzers to perform measurements, checks, and adjustments of the combustion process. This device provides precise information about the composition of flue gases, thereby contributing to optimizing the combustion process through the incorporated sensors.

The devices used for analyzing the flue gases (produced by Testo [7]) were also important for the calibration of automatic control and command system. They also allowed the verification of predefined functional parameters and ensured compliance with technical and legal limits.

The analysis of the combustion process involved visual observations, as well, using the sight glass as a supplementary measure to validate adjustments. This was helpful in interpreting parameters derived from monitoring the evolution of exhaust gases.

The gas analyzer sensors are designed to detect concentrations of gases such as carbon dioxide (CO_2), carbon monoxide (CO), oxygen (O_2), and other relevant parameters, like temperature of the combustion gases. Additionally, a temperature sensor has been integrated into the exhaust area, providing essential information about the temperature of the flue gases but also with a role in combustion control. This is crucial for maintaining temperatures within optimal limits, preventing condensation and improving the overall energy efficiency of the biomass combustion system.

The quality of the pellets has a direct impact on the measured values [8,9,10], as presented in various studies. The monitoring process of one commercial prototype was carried out using high-quality pellets, produced by a local wood waste processing factory, with low moisture and ash content, enabling an analysis at a high combustion efficiency level.

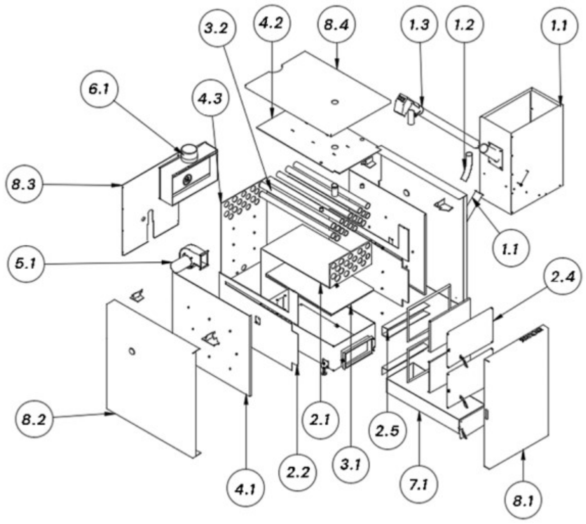

Fig. 1. Exploded-view drawing of the prototype with the main subsystems

1.1. Pellet reservoir; 1.2. Pellet feeder reduction (flexible feeding pipe); 1.3. Boiler pellet feeder (screw conveyor); 2.1. Top and bottom part of the combustion chamber (CC); 2.2. Left side of CC; 2.3. Dome-type burner; 2.4. Upper and lower doors; 2.5. Door frame; 3.1. Heat exchanger tubes; 3.2. Heat exchanger panel; 4.1. Left side water jacket; 4.2. Upper water jacket; 4.3. Lower water jacket; 5.1. Air supply system; 6.1. Flue gas box; 7.1. Ash box; 8.1. Front cover; 8.2. Side cover; 8.3. Rear cover.

In order for combustion to be as complete as possible and close to the ideal process, a larger quantity of air than the minimum calculated one was introduced because, in reality, achieving a perfectly homogeneous mixture of fuel with the introduced oxygen is impossible, especially in the case of solid fuel combustion. The additional quantity of air introduced represents the excess air, which mathematically results from the ratio between the actual quantity of air supplied for combustion and the minimum required quantity calculated. The accepted excess air coefficient has values greater than unity, ranging between 1.3 and 2. The variation in excess air values is influenced by transient processes occurring in the combustion process, such as fuel injection, ignition and the fuel extinguishing phase, and changes in power levels. The chosen values from the mentioned ranges depend on the quality and nature of the fuel, as well as the combustion process in the boiler's combustion chamber.

During the measurements, in order to observe the boiler's behavior, the operation was in continuous dynamics, without a stationary operating process. Under these conditions, the excess air coefficient varied in the range of 1.9 to 3.3.

To achieve high efficiency for the entire boiler, adjustments were made so that the temperature of the flue gases was maintained between of 110 and 150 °C. Analyses conducted in multiple operating scenarios reflected a combustion efficiency that varied within narrow limits between 0.89 and 0.92, despite frequently passing through transient regimes.

The authors of this work have monitoring of the commercial prototype to develop its EB for two operating regimes under the following conditions:

- *Monitoring Case 1*:
  - Fuel used: wood pellets (70% beech and 30% spruce) with a calorific value of 4.6 kWh/kg;
  - Fuel feed: cyclical fuel feeding with a feed period of 7 seconds followed by a 13-second pause, at a mass flow rate of 8.23 g/s, equivalent to 10.37 kg/h;
  - Circulation pump: maintains a constant water flow in the consumer circuit at 3.323 m^3/h.
- *Monitoring Case 2*:
  - Fuel used: wood pellets (70% beech and 30% spruce) with a calorific value of 4.6 kWh/kg;
  - Fuel feed and pump flow: variable, with values set by the automation system.

In Figure 2, the EB outline and the measurement points are illustrated.

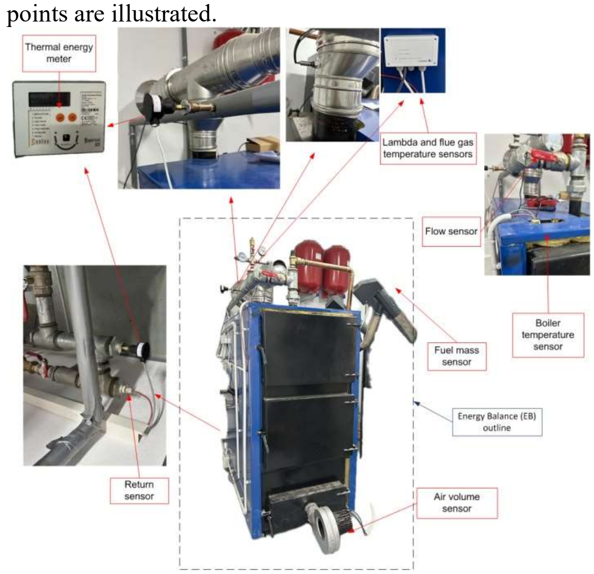

Fig. 2. EB outline and the measuring points

2. THE MATHEMATICAL MODEL FOR THE EB OF THE ANALYZED COMMERCIAL PROTOTYPE

For the balance outline of the commercial prototype presented above, the equation for the EB is [11]:

$$Q_f + W_{EE} = W_{TE} + \Delta Q_{fg} + \Delta Q_{hl} \qquad (1)$$

which includes the following terms:

a) Q_f [kWh] – heat input of the fuel

$$Q_f = m_f H_f \qquad (2)$$

where,
m_f [kg] – mass of fuel introduced into the boiler;
H_f [kWh/kg] – the heat value of a fuel;

b) W_{EE} [kWh] – electric power consumption of the system, indicated by the electric energy meter;

c) W_{TE} [kWh] – thermal energy produced by the system, measured by the thermal energy meter;

d) ΔQ_{fg} [kWh] – heat loss with flue gases:

$$\Delta Q_{fg} = m_{fg} \cdot c_{fg} \cdot (t_{fg} - t_a) \,/\, 3600 \qquad (3)$$

where,

m_{fg} [kg] - the quantity of flue gases (mass) exhausted from the boiler;

c_{fg} [kJ/kg·grd] - specific heat capacity of flue gases;

t_{fg} [ºC] - flue gases outlet temperature;

t_a [ºC] - boiler inlet air temperature;

e) ΔQ_{hl} [kWh] – heat losses through boiler walls, doors, ash, etc.

3. EBS FOR THE COMMERCIAL PROTOTYPE

Within the undertaken study, the EB of the analyzed system was conducted for various operating regimes characterized by different values of thermal power produced by it. The EB was performed based on the previously outlined, utilizing the elaborated monitoring system. Experimentally measured values were input into the mathematical model of the EB, resulting in the outcomes presented in the following sections.

3.1. The monitoring conducted for Case 1

The monitoring for Case 1 aimed to establish an EB for the commercial prototype, analyzing its operation over study duration of 1 hour under the following operating conditions:

- The fuel used consists of wood pellets (70% beech and 30% fir) with a calorific power of 4.6 kWh/kg;
- Fuel supply is cyclic, with a feeding period of 7 seconds followed by a 13 second pause, at a fuel mass flow rate of 8.23 g/s, equivalent to 10.37 kg/h;
- The circulation pump ensures a constant water flow rate in the consumer circuit of 3.323 m³/h.

The measured values are presented in Table 1.

Table 1. Measured values for Case 1

No.	h	m	T.E.	t_{fha}	t_{rha}	T.P.	F.G.
			[GJ]	[°C]	[°C]	[kW]	[m³/h]
1	17	00	1.939	64.3	53.8	40.1	116
2	17	10	1.957	64.8	54.6	38.32	153
3	17	20	1.977	65	56.1	35.44	150
4	17	30	1.999	66	57.1	34.61	105
5	17	40	2.02	67	57.9	33.58	95
6	17	50	2.041	67.9	59.1	33.29	94
7	18	00	2.062	69	59.2	36.69	99.4
No.	h	m	t_{fg}	t_a	O_2	E.E.	
			[°C]	[°C]	[%]	[kWh]	
1	17	00	136	20.7	12.7	20.02	
2	17	10	143.7	21.1	13.3	20.07	
3	17	20	123.4	20.4	13.3	20.12	
4	17	30	120.5	20.8	13.4	20.17	
5	17	40	121	21.5	12.6	20.22	
6	17	50	122	22	12	20.27	
7	18	00	122.8	22.1	11.3	20.32	

Where in addition to the ones previously presented:

h : m – hour : minute of the measurement;

T.E. - indication of the thermal energy meter;

t_{fha} - temperature of the flow heating agent;

t_{rha} - temperature of the return heating agent;

T.P. – thermal power;

F.G. – flue gas flow rate;

O_2 – oxygen content in flue gases;

E.E. - indication of the electric energy meter.

By applying the mathematical model of the EB, we calculated the characteristic values presented in Table 2 for the quantities.

Table 2. Calculated values for Case 1

No.	from	to	m_f	Q_f	W_{EE}	W_{TE}
	[h:m]	[h:m]	[kg]	[kWh]	[kWh]	[kWh]
1	17:00	17:10	1.728	7.950	0.05	5.00
2	17:10	17:20	1.728	7.950	0.05	5.56
3	17:20	17:30	1.728	7.950	0.05	6.11
4	17:30	17:40	1.728	7.950	0.05	5.83
5	17:40	17:50	1.728	7.950	0.05	5.83
6	17:50	18:00	1.728	7.950	0.05	5.83
		TOTAL	10.370	47.701	0.30	34.17
No.	from	to	FG	m_{fg}	ΔQ_{fg}	ΔQ_{hl}
	[h:m]	[h:m]	[kg/h]	[kg]	[kWh]	[kWh]
1	17:00	17:10	161.40	26.90	0.867	2.133
2	17:10	17:20	181.80	30.30	1.038	1.407
3	17:20	17:30	153.00	25.50	0.734	1.155
4	17:30	17:40	120.00	20.00	0.557	1.610
5	17:40	17:50	113.40	18.90	0.526	1.641
6	17:50	18:00	116.04	19.34	0.540	1.626
		TOTAL	845.64	140.94	4.262	9.572

The parameters of the EB for the commercial prototype, under the operating conditions mentioned earlier, obtained during the monitoring for Case 1, are synthetically presented in Table 3.

Table 3. The parameters of the EB obtained during the monitoring for Case1

Parameter	[kWh]	[MJ]	[%]
Input Energy, of which:	48.001	172.804	100
Q_f	47.701	171.724	99.38
W_{EE}	0.300	1.080	0.62
Output Energy, of which:	48.001	172.804	100
W_{TE}	34.170	123.000	71.18
ΔQ_{fg}	4.262	15.343	8.88
ΔQ_{hl}	9.572	34.461	19.94

A Sankey diagram of EB conducted during the monitoring for Case 1 is presented in Figure 3.

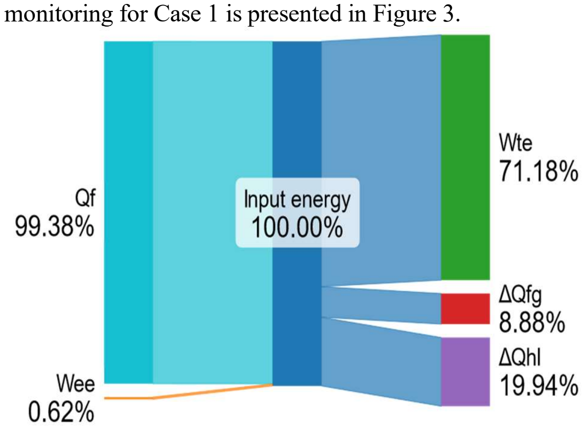

Fig. 3. Sankey diagram for the EB performed for Case 1

Based on the Sankey diagram from Figure 3, developed for the monitoring commercial prototype, operating under the specified conditions, achieved an efficiency of 71.18%. Heat losses with flue gases accounted for 8.88%, while thermal losses of the boiler through walls and doors were 19.94%.

3.2. The monitoring conducted for Case 2

The EB prepared for the commercial prototype, based on the monitoring for Case 2, was conducted under similar operating conditions as in the previously monitoring, with the difference that fuel supply and circulation pump flow rate were variable, according to the values set by the prototype automation system. The measured values are presented in Table 4.

Table 4. Measured values on for Case 2

No.	h	m	T.E.	t_{fha}	t_{rha}	T.P.	F.G.
			[GJ]	[°C]	[°C]	[kW]	[m3/h]
1	13	00	2.429	46.0	32.4	49.460	150
2	13	10	2.458	47.5	35.1	45.776	135
3	13	20	2.487	49.4	33.6	56.365	135
4	13	30	2.518	47.9	36.0	44.004	135
5	13	40	2.544	53.1	39.8	46.554	150
6	13	50	2.577	56.7	42.1	53.155	135
7	14	00	2.608	58.2	43.4	52.833	130
No.	h	m	t_{fg}	t_a	O_2	m_{tf}	E.E.
			[°C]	[°C]	[%]	[kg]	[kWh]
1	13	00	146	20.0	11.6	0	31.07
2	13	10	140.7	20.6	10.4	2.501	31.13
3	13	20	140.0	20.1	9.5	4.938	31.19
4	13	30	140.0	20.0	10.5	7.341	31.24
5	13	40	148.3	20.6	8.9	10.032	31.29
6	13	50	148.8	20.6	9.0	12.781	31.35
7	14	00	147.6	21.5	8.7	15.470	31.40

Where in addition to the ones previously presented:

m_{tf} - total mass of fuel introduced

The characteristic parameters of the EB were obtained based on the presented mathematical model and are presented in Table 5.

Table 5. Calculated values for Case 2

No.	from	to	m_f	Q_f	W_{EE}	W_{TE}
	[h:m]	[h:m]	[kg]	[kWh]	[kWh]	[kWh]
1	13:00	13:10	2.501	11.505	0.06	8.06
2	13:10	13:20	2.437	11.210	0.06	8.06
3	13:20	13:30	2.403	11.054	0.05	8.61
4	13:30	13:40	2.691	12.379	0.05	7.22
5	13:40	13:50	2.749	12.645	0.06	9.17
6	13:50	14:00	2.689	12.369	0.05	8.61
TOTAL			15.470	71.162	0.33	49.72
No.	from	to	FG	m_{fg}	ΔQ_{fg}	ΔQ_{hl}
	[h:m]	[h:m]	[kg/h]	[kg]	[kWh]	[kWh]
1	13:00	13:10	171.00	28.50	1.003	2.506
2	13:10	13:20	162.00	27.00	0.906	2.308
3	13:20	13:30	162.00	27.00	0.905	1.588
4	13:30	13:40	171.00	28.50	0.956	4.251
5	13:40	13:50	171.00	28.50	1.017	2.522
6	13:50	14:00	159.00	26.50	0.949	2.859
TOTAL			996.00	166.00	5.736	16.033

The parameters of the EB for the commercial prototype, under the operating conditions mentioned earlier, obtained during the monitoring for Case 2, are synthetically presented in Table 6.

Table 6. The parameters of the EB obtained during the monitoring for Case 2

Parameter	[kWh]	[MJ]	[%]
Input Energy, of which:	71.492	257.371	100
Q_f	71.162	256.183	99.54
W_{EE}	0.330	1.188	0.46
Output Energy, of which:	71.492	257.371	100
W_{TE}	49.72	179.000	69.55
ΔQ_{fg}	5.736	20.651	8.02
ΔQ_{hl}	16.033	57.720	22.43

A Sankey diagram of EB conducted during the monitoring for Case 2 is presented in Figure 4.

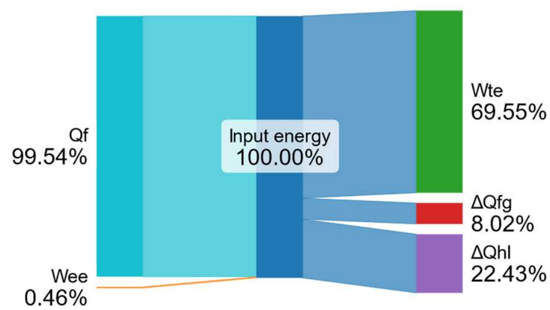

Fig. 4. Sankey diagram for the EB performed for Case 2

In conclusion, the commercial prototype, operating under the specified conditions, during the monitoring for Case 2, achieved an efficiency of 69.55%. Heat losses with flue gases accounted for 8.02%, while total thermal losses from the boiler through walls and doors were 22.43%.

4. MONITORING HEAT LOSSES OF THE COMMERCIAL PROTOTYPE

The EB of the commercial prototype highlighted that the prototype's efficiency is largely influenced by the relatively high level of heat losses at the boiler level (through the boiler walls and its doors). Consequently, monitoring these losses is necessary to identify specific areas of the boiler which is susceptible to heat loss. In order to achieve this, we decided to use an external thermal camera, specifically the Topdon TC002 [12].

The TC002 thermal imaging camera offers high precision for temperature detection and thermal insulation inspection. It features ultra-high resolution, providing clear and detailed thermal images. The camera has a temperature detection range of ±2°C with an accuracy of 0.1°C. With a relatively low energy consumption of 0.35 W, the camera can be used for extended periods. The TC002 camera can be employed for a relatively wide temperature range from -20°C to 550°C, enabling secure temperature readings from a distance. All these features led us to choose the Topdon TC002 thermal imaging camera for monitoring the heat losses of the analyzed commercial prototype.

4.1. The results of the thermal imaging monitoring

Monitoring the heat losses was conducted under steady-state operating conditions of the commercial prototype, at a thermal load of 40 kW. Using the thermal imaging camera, we recorded images of the boiler on all its surfaces, identifying, on each surface, the hot spots with high heat loss values. In Figure 5 ÷ 11, we present some of the images captured during the monitoring process.

Fig. 5. – The entire boiler

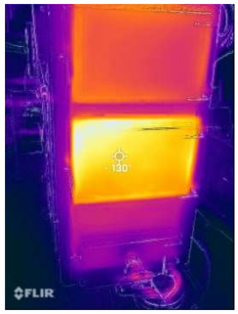

Fig. 6. – The lower door

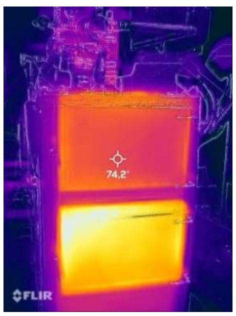

Fig. 7 – The upper door

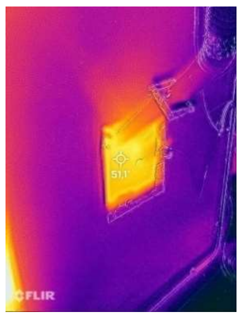

Fig. 8 – The right side

Fig. 9 – The left side

Fig. 10 – The back side

Fig. 11 – The path of the flue gases

Through this monitoring, we have identified critical areas through which the system predominantly loses heat. Below, we present these areas in descending order of measured temperatures:

- Lower door - measured temperature: 130 ºC (Figure 6);
- Flue gas path: 94.9 ºC (Figure 11);
- Upper door: 74.2 ºC (Figure 7);
- Area behind the boiler for flue gas discharge: 70.7 ºC (Figure 10);
- Flame viewing port (left side surface of the boiler): 52.5 ºC (Figure 9);
- Fuel feeding area (right side surface): 51.1 ºC (Figure 8).

To enhance the performance of the analyzed system and increase its efficiency beyond the values identified in the conducted EB, it is essential to reduce heat losses. This involves improving thermal insulation in the aforementioned areas: boiler doors and side surfaces in the flame viewing port area and the fuel introduction zone.

5. CONCLUSION

The implementation of testing, monitoring, and optimization activities for analyzed system, allows the formulation of the following conclusions:

- The efficiency of the analyzed system was 71.18% during the monitoring for Case 1 and 69.55% for Case 2. Heat losses with combustion gases accounted for 8.88% and 8.02%, while thermal losses through the boiler walls and doors were 19.94% and 22.43%, respectively. Therefore, the analyzed system efficiency is significantly influenced by the relatively high level of heat losses from the boiler (through its walls and doors). Consequently, optimizing the analyzed system requires identifying the specific areas of heat loss in the boiler and implementing measures to reduce these losses.
- The analyzed combustion efficiency throughout the monitoring varies in the range of 0.89 to 0.92. The variations are influenced by the frequency of transitioning through transient states. It is recommended to operate for as long as possible in the same power level and avoid repeated cycles of pellet ignition and extinguishing. This consistent operating mode is defined by the characteristic of the consumer to either have or not have thermal energy storage capacities, which handle peaks and gaps in thermal load imposed during operation.
- For the optimization of the analyzed system, it is necessary to enhance its energy performance by increasing the efficiency beyond the values identified in the conducted monitoring, achieved through the reduction of heat losses. This involves improving thermal insulation in the previously mentioned hot zones: the boiler doors and the side surfaces in the flame view area and in the fuel feeding area.
- The future research will focus on monitoring the biomass system in order to optimize it by increasing its energy efficiency.

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