OPTIMIZATION OF A PROTOTYPE BIOMASS SYSTEM

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Abstract – This paper presents the results of analysing the energy performance improvement of the final commercial prototype (FCP), based on the monitoring results discussed in the previous paper regarding the commercial prototype (CP). Similar to the previous paper, the energy balance (EB) was carried out according to the regulation no. 245 established by the Romanian Agency for Energy Conservation (RAEC). The monitoring system was the one used previously. The mathematical model used for the optimised energy balance (OEB) of the FCP is also presented. We carried out the OEB of the FCP for a few different operating conditions, of which we present two, differing also by the type of fuel: corn grains and wood pellets (70% beech and 30% fir) respectively. The FCP monitoring process was carried out again after improving its thermal insulation, by infrared thermal vision. The experimental results were used as input for the mathematical model, and the results are presented in the conclusions.

Keywords: prototype optimization, energy balance, efficiency of biomass heating system, experimental measurements analysis.

Abbreviations: EB - energy balance; OEB – optimized energy balance, CP – commercial prototype, FCP – final commercial prototype.

1. INTRODUCTION

The gradual reduction of fossil fuels utilisation and their replacement with renewable energy sources, high calorific value biomass included, obviously while obeying the environment protection norms [1,2], is one of the objectives to be obtained for reaching the EU climatic neutrality by 2050. The increase of biomass utilisation is highlighted in many studies, such as [3,4,5,6], and the technological principals are well known [4,7,8,9].

The current paper is the second stage of a study that consists of many parts, of which [10] presented several conclusions of the energy efficiency analyses by monitoring the relevant parameters of a biomass fired system.

For the unoptimized commercial prototype presented in [10], the heat loss values for the boiler through its walls and door had relatively high values: 19.94% (9.572 kWh) and 22.43% (16.033 kWh) for the two thermal loads of 33÷40 kW and 44÷53 kW respectively. Some measures have been taken to reduce these thermal losses in the areas with high heat losses (lateral walls, doors, flame visor, fuel input area) and improve the energy performance of the optimized commercial prototype.

This paper presents a summary of the two different operating regimes, named here Case A and Case B.

The devices used for analysing the flue gas composition were those used before implementing the optimisation measures, namely incorporated sensors and gas analysers produced by Testo [11] necessary to validate the predefined operational parameters and the complying with the legal technical limits. The values of carbon dioxide (CO_2), carbon monoxide (CO), and oxygen (O_2) concentrations have been monitored, as well as the flue gas temperature.

The increases of the FCP by keeping the temperature within the optimal limits by regulating the air and fuel inputs have been improved by implementing a fuzzy logic in the monitoring and control software.

The FCP monitoring results presented in this paper, for both cases mentioned above, were carried out in November 2023, in the following operating conditions:

- Optimized Case A:
  - the fuel was corn grains with a calorific value of 4.5 kWh/kg;
  - the fuel was supplied in cycles, with a 16 s input time and a 4 s break, at a mass flow rate of 5.05 g/s, which means 14.544 kg/h;
  - the volume flow rate in the heating loop was constant at 3.323 m^3/h.
- Optimized Case B:
  - the fuel was wood pellets (70% beech and 30% fir), with a calorific value of 4.6 kWh/kg;
  - the fuel input was regulated by the control system based on fuzzy logic and continuously recorded;
  - the volume flow rate in the heating loop was also regulated by the control system.

For the energy balance we used the same border limits and mathematical model as in paper [10].

2. OPTIMIZED ENERGY BALANCES FOR THE FCP

Based on the results presented in [10], the improvement of the energy performance was validated by carrying out the OEB.

The FCP OEB was carried out for different operating conditions, at different supplied thermal powers.

The OEB was carried out using the monitoring system completed by the research team [10]. The experimental measured values were used in the above mentioned OEB mathematical model, the results being given below.

2.1. Results for Case A

For Case A, the monitoring results were obtained in November 2023. A sample for one hour of operation under the conditions presented in chapter 1 are given in Table 1.

Table 1. Measured values for Case A of the FCP

No.	h		m	T.E.	t_{fha}	t_{rha}	T.P.	F.G.
				[GJ]	[°C]	[°C]	[kW]	[m^3/h]
1	14		0	4.963	61.3	50.9	36.38	112
2	14		10	4.990	64.3	51.4	44.03	116
3	14		20	5.021	65.4	51.0	48.53	120
4	14		30	5.048	64.4	50.9	45.97	117
5	14		40	5.078	65.5	51.0	49.64	149
6	14		50	5.107	65.1	51.0	48.33	120
7	15		0	5.137	65.2	51.1	48.37	121

No.	h		m	t_{fg}	t_a	O_2	E.E.
				[°C]	[°C]	[%]	[kWh]
1	14		0	136.9	18.8	10.90	47.59
2	14		10	140.0	19.0	10.60	47.63
3	14		20	147.1	19.2	11.82	47.70
4	14		30	140.2	19.8	10.67	47.74
5	14		40	128.0	19.8	11.02	47.79
6	14		50	148.7	19.9	11.61	47.82
7	15		0	151.1	19.6	11.24	47.87

Where: h:m – hour:minute of the measurement;
T.E. - indication of the thermal energy meter;
t_{fha} - heating agent flow temperature;
t_{rha} - heating agent return temperature;
T.P. – thermal power;
F.G. – flue gas volume flow rate;
O_2 – oxygen content in flue gases;
E.E. - indication of the electric energy meter.

The characteristic values presented in Table 2 are calculated by applying the mathematical model of the OEB.

Table 2. Calculated values for Case A of the FCP

No.	from	to	m_f	Q_f	W_{EE}	W_{TE}
	[h:m]	[h:m]	[kg]	[kWh]	[kWh]	[kWh]
1	14:00	14:10	2.424	10.908	0.04	7.50
2	14:10	14:20	2.424	10.908	0.07	8.61
3	14:20	14:30	2.424	10.908	0.04	7.50
4	14:30	14:40	2.424	10.908	0.05	8.33
5	14:40	14:50	2.424	10.908	0.03	8.06
6	14:50	15:00	2.424	10.908	0.05	8.33
TOTAL			14.544	65.448	0.280	48.33

No.	from	to	FG	m_{fg}	ΔQ_{fg}	ΔQ_{hl}
	[h:m]	[h:m]	[kg/h]	[kg]	[kWh]	[kWh]
1	14:00	14:10	136.80	22.80	0.752	2.696
2	14:10	14:20	141.60	23.60	0.798	1.569
3	14:20	14:30	142.20	23.70	0.847	2.601
4	14:30	14:40	159.60	26.60	0.895	1.730
5	14:40	14:50	161.40	26.90	0.813	2.069
6	14:50	15:00	144.60	24.10	0.867	1.757
TOTAL			886.20	147.70	4.973	12.421

After optimization based on the conclusions from the previous paper [10], the parameters of the OEB for the FCP obtained during the monitoring for Case A under the operating conditions above are synthetically presented in Table 3.

Table 3. The parameters of the OEB obtained during the monitoring for Case A of the FCP

Parameter	[kWh]	[MJ]	[%]
Input Energy, of which:	65.73	236.62	100
Q_f	65.45	235.61	99.57
W_{EE}	0.28	1.01	0.43
Output Energy, of which:	65.73	236.62	100
W_{TE}	48.33	174.00	73.54
ΔQ_{fg}	4.97	17.90	7.56
ΔQ_{hl}	12.42	44.72	18.90

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

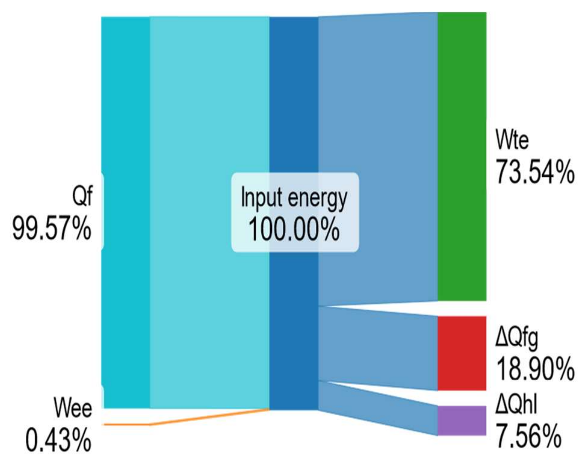

Fig. 1. Sankey diagram for the energy balance of Case A

Based on the Sankey diagram in Figure 1, the FCP, operating under the specified conditions achieved an efficiency of 73.54%. Heat losses with flue gases accounted for 18.90%, while thermal losses of the boiler through walls and doors were 7.56%.

2.2. Results for Case B

The monitoring for Case B was also carried out in November 2023, the results being used for the FCP OEB by implementing:

- reduction of heat losses through walls and door by adding thermal insulation;
- input an optimised fuzzy logic into the control system.

A one hour sample of results for Case B under the operating conditions mentioned above are given below. The wood pellets supply was regulated by the control system based on the new fuzzy logic.

The recorded values are given in Table 4.

Table 4. Measured values for Case B of the FCP

No.	h	m	T.E.	t_{fha}	t_{rha}	T.P.	F.G.
			[GJ]	[°C]	[°C]	[kW]	[m^3/h]
1	12	10	4.771	53	41	43.6	118
2	12	20	4.799	54.5	43.8	41.21	121
3	12	30	4.81	56.7	47.4	33.56	121
4	12	40	4.837	60.5	50.8	35.22	124
5	12	50	4.859	62.8	53.1	36.21	125
6	13	0	4.878	63.1	55.6	29.34	135
7	13	10	4.891	64.5	58	29.33	128
No.	h	m	t_{fg}	t_a	O_2	E.E.	
			[°C]	[°C]	[%]	[kWh]	
1	12	10	140	19.8	12.6	47.1	
2	12	20	140	20	12.74	47.15	
3	12	30	138.8	20.2	13.6	47.18	
4	12	40	137.5	20.7	14.42	47.23	
5	12	50	158.3	21	13.81	47.28	
6	13	0	139.2	21.6	15.41	47.33	
7	13	10	128.6	21.9	15.96	47.38	

The values presented in Table 5 were obtained using the OEB mathematical model.

Table 5. Calculated values for Case B

No.	from	to	m_f	Q_f	W_{EE}	W_{TE}
	[h:m]	[h:m]	[kg]	[kWh]	[kWh]	[kWh]
1	12:10	12:20	1.169	5.377	0.05	7.78
2	12:20	12:30	1.938	8.915	0.03	3.06
3	12:30	12:40	1.638	7.535	0.05	7.50
4	12:40	12:50	1.582	7.277	0.05	6.11
5	12:50	13:00	1.633	7.512	0.05	5.28
6	13:00	13:10	1.581	7.273	0.05	3.61
		TOTAL	9.541	43.889	0.280	33.33
No.	from	to	FG	m_{fg}	ΔQ_{fg}	ΔQ_{hl}
	[h:m]	[h:m]	[kg/h]	[kg]	[kWh]	[kWh]
1	12:10	12:20	143.40	23.90	0.803	-3.153
2	12:20	12:30	145.20	24.20	0.812	5.078
3	12:30	12:40	147.00	24.50	0.812	-0.727
4	12:40	12:50	149.40	24.90	0.813	0.403
5	12:50	13:00	156.00	26.00	0.998	1.286
6	13:00	13:10	157.80	26.30	0.864	2.847
		TOTAL	898.80	149.80	5.101	5.734

The parameters of the OEB for the FCP, under the above-mentioned operating conditions, obtained monitoring Case B, are synthetically presented in Table 6.

Table 6. The parameters of the OEB obtained during the monitoring for Case B of the FCP

Parameter	[kWh]	[MJ]	[%]
Input Energy, of which:	44.17	159.01	100
Q_f	43.89	158.00	99.37
W_{EE}	0.28	1.01	0.63
Output Energy, of which:	44.17	159.01	100
W_{TE}	33.33	120.00	75.47
ΔQ_{fg}	5.10	18.36	11.55
ΔQ_{hl}	5.73	20.64	12.98

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

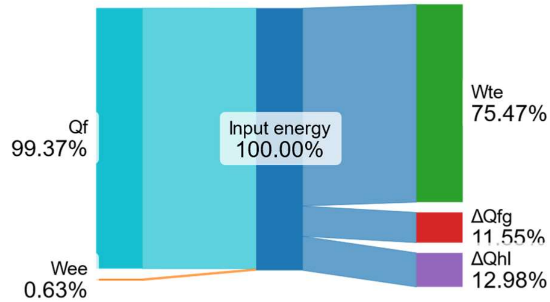

Fig. 2. Sankey diagram for the energy balance of Case B

In conclusion, the FCP, operating under the specified conditions during the monitoring in Case B, achieved an efficiency of 75.47%. Heat losses with flue gases accounted for 11.55%, while total thermal losses from the boiler through walls and doors were 12.98%.

3. MONITORING THE HEAT LOSSES

The energy balance of the commercial prototype (CP), as it was presented in [10], highlighted that the prototype's efficiency is largely influenced by the relatively high heat losses at the boiler level in different parts.

According to the conclusions formulated in the previous article [10], improvement of the thermal insulation of the FCP doors and lateral surfaces, in the area of the flame sight glass and also in the fuel feeding point, was improved.

In this optimized version, we resumed the monitoring process of FCP with the enhanced thermal insulation, using the same equipment, an external thermal camera, specifically the Topdon TC002 [12], which offers high precision for temperature detection and thermal insulation inspection.

3.1. Reassessment of heat losses using thermal imaging monitoring

Monitoring the heat losses was conducted under steady-state operating conditions of the FCP, at the same thermal load of 40 kW. Using the thermal imaging camera, we recorded images of the boiler on all its surfaces, identifying and comparing with the values from the previous article.

In the following Figures 3 ÷ 8, we show the thermal images after improving the insulation in the critical points during the monitoring process.

Fig. 3 – The entire boiler

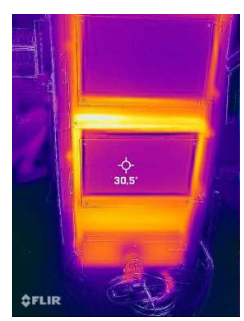

Fig. 4 – The lower door

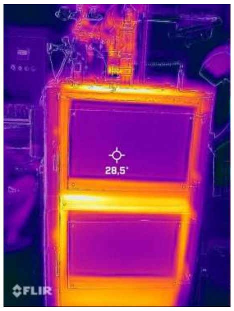

Fig. 5 – The upper door

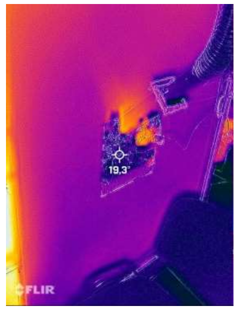

Fig. 6 – The right side

Fig. 7 – The left side

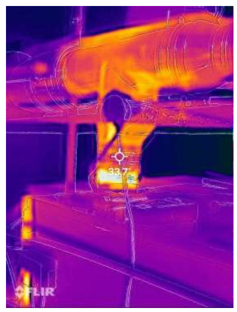

Fig. 8 – The flue gases duct

Through this reassessment we have identified a substantial reduction of the temperature values in these areas, compared to the values obtained previously in [10].

Below, we present the critical areas in descending order of the new measured temperatures:

- Lower door - measured temperature: 30 ºC (Figure 4);
- Flue gas duct: 33.7 ºC (Figure 8);
- Upper door: 28.5 ºC (Figure 5);
- Flame viewing port (left side surface of the boiler): 21.5 ºC (Figure 7);
- Fuel feeding area (right side surface): 19.3 ºC (Figure 6).

4. CONCLUSION

After implementing the optimization measures based on the conclusions from the previous paper [10], monitoring the FCP under the operating conditions mentioned in this paper, allows the formulation of the conclusions below.

The thermal efficiency of the FCP was 73.54% for Case A and 75.47% for Case B, the values being relatively close for using corn grains and wood pellets, showing that the FCP can be operated at high efficiencies with both fuels.

By decreasing the temperatures in the sensitive places, the heat losses have been reduced from 19.94% (9.572 kWh) to 12.98% (5.73 kWh) for a load of about 40 kW for the same fuel under similar conditions.

Table 7 shows a comparison of temperatures before and after the improvement of the thermal insulation.

Table 7. FCP temperature before and after improving the thermal insulation

No.	Surface / Element	Temperatures [°C]	
		before	after
1	Lower door	130	30.5
2	Flue gas duct	94.9	33.7
3	Upper door	74.2	28.5
4	Flame viewing port	52.5	21.5
5	Fuel feeding area	51.1	19.3

The implementation of the optimisation measures for increasing the system efficiency, identified in [10], increased the FCP efficiency from 69.55% (Case 1 in [10]) and 71.18% (Case 2 in [10]) respectively, to 75.47% (Case B) for the same fuel type. Table 8 shows comparative EB values from [10] and those monitored for the FCP in this paper.

Table 8. Comparison of the EB and OEB parameters

	CP				FCP	
	Case 1 [10]		Case 2 [10]		Case B	
P	[kWh]	[%]	[kWh]	[%]	[kWh]	[%]
I E:	48.001	100	71.492	100	44.17	100
Q_f	47.701	99.38	71.162	99.54	43.89	99.37
W_{EE}	0.300	0.62	0.330	0.46	0.28	0.63
OE:	48.001	100	71.492	100	44.17	100
W_{TE}	34.17	71.18	49.72	69.55	33.33	75.47
ΔQ_{fg}	4.262	8.88	5.736	8.02	5.10	11.55
ΔQ_{hl}	9.572	19.94	16.033	22.43	5.73	12.98

Where, in addition to those previously presented:
P – parameter of EB (OEB);
IE - Input Energy,
OE - Output Energy.

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