TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 125, 2013, 55–65

TOMASZ TURZYŃSKI*, DARIUSZ KARDAŚ

Experimental research on helical coil biomass boiler with oil as a heating fluid

The Szewalski Institute of the Fluid-Flow Machinery of the Polish Academy of Sciences, Fiszera 14, 80-231 Gdańsk, Poland

Abstract

The aim of the paper is to present the results of experimental research conducted on helical coil biomass boiler with oil as a heating fluid, which is a central unit of co generative micro power-plant designed and tested at the Institute of Fluid-Flow Machinery in Gdańsk. Experimental data has been used to work out characteristics of the device in terms of power, efficiency and oil parameters for moderate/high excess air numbers and fuel flow rates. Furthermore, during the research the authors came across various obstacles, which can be easily eliminated in the future prototypes by applying presented changes in construction.

Keywords: Thermal oil; Boiler; Characteristics; Helical coil biomass

Nomenclature

C_p – specific heat of thermal oil
E – plate type exchanger
G – generator
K, S – type and placement of thermocouple sensor
P – heating power of the boiler, kW
Q_{oil} – oil flow rate, kg/h
S_{fg} – flue gas loss
S_{im} – imperfect combustion loss
S_r – radiation and convection loss
S_u – unburnt fuel loss

---

[*] Corresponding author. E-mail address: tturzynski@imp.gda.pl

T – turbine
T_{amb} – ambient temperature
T_{gas} – temperature of the flue gas
T_{in} – oil temperature on the inlet of the coil exchanger
T_{mean} – mean temperature of oil inside the coil heat exchanger
T_{out} – oil temperature on the outlet of the coil exchanger
ΔT – difference between T_{in} and T_{out}

Greek symbols

η – thermal efficiency of the boiler
λ – air excess number
[ ] – volumetric concentration of the species
4-20mA – signal type and placement of air, flue gas and oil flowmeters

1 Introduction

Biomass, among other renewable fuels, is a very specific and troublesome source of energy. Combustion of biomass is connected with many issues rendering classical approaches to boilers not as accurate as they used to be for the coal-burning units. Therefore an experimental research was performed, which aim was to design a small scale biomass boiler unit characterized by a high efficiency and output parameters. The boiler unit is to be a heat source for cogenerative combined heat and power (CHP) microplant based on the organic Rankine cycle (ORC) and a custom-made steam turbine that powers the generator. In this section, the heating agent is a low-boiling fluid HFE7100, which evaporates while receiving heat from the oil and powers the turbine. Producing heat and power in microscale is dedicated for small households or farms and as it is, both the ORC section and helical coil boiler are unique constructions in their field.

2 Boiler construction

The boiler unit consists of a coaxial, double helical coil as the heat exchanger and a retort-type biomass burner (located at the bottom of the unit) connected with a small biomass reservoir. In this particular installation thermal oil was used as the heating agent due to high output parameters. The hot flue gas from the burner flows up through the smaller coil, then changes direction at the top of the boiler and flows downward between both coils and finally flows up to the stack. On the other hand, the thermal oil inlet is located at the bottom of the outer helical coil. The oil travels up to the inner coil and then down to the outflow. This configuration is basically a counter current exchanger with counter/cocurrent section between both coils. Spiral tube heat exchanger prevents thermal oil from overheating, which otherwise could have taken place for instance in a shell-and-tube type exchanger. The flue gas flow diagram, as well as boiler construction

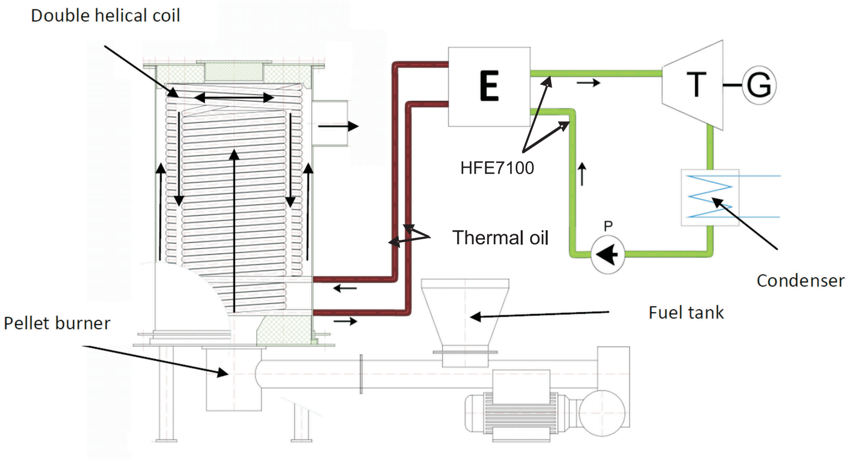

Figure 1. Boiler and ORC conceptual layout with flue gas flow diagram: E – plate heat exchanger, T – turbine, G – generator, P – pump.

and micro CHP section layout was presented in Fig. 1. This construction is quite unusual in comparison to typical coil heat exchangers [1,2]. Firstly, usually this type of exchanger is being used with natural gas burners in horizontal arrangement. Secondly, in general the flue gas flow is divided between coils to create only co-current or counter-current exchanger.

3 Measurement system

Dedicated measurement system enables use of the boiler unit without its cooperation with ORC section. In presented herein experimental research the heat from thermal oil was transferred to ethylene glycol solution in a shell&coil type exchanger and cooled in air cooler. In this configuration it is possible to measure thermal balance in terms of fuel, oil and air mass flows. In this type of a burner both, air and fuel, are being transported to the boiler together in a mixed bed. In this situation, it is highly probable, that air flow affects the fuel mass flow in some degree due to changes in combustion bed. In this study however it was impossible to unequivocally determine the actual fuel flow and so, based upon the knowledge of the amount of fuel transported through the burner without combustion per hour, an estimated value of fuel flow rate was used. This particular burner operates via run/stop feature only, so the fuel flow rate is not continuous but discrete, nevertheless, considering a large thermal inertia of the boiler itself, this has not been an issue.

Inlet air flow was measured on straight pipe segment between the burner and a fan. In this case thermal flow meter was used. This device is powered from external 24 V power supply and gives the signal of 4-20 mA. Similar flow meter was installed in the stack for flue gas flow measurement. The mass flow of thermal oil is being measured on the outlet from the boiler. In this case a GPI GBT-075Hx-x 3/4" turbine flow meter was used. It is commonly known that these types of flow meters are very sensitive to viscosity so the oil type heating agent will cause problems. However, while the temperatures are moderate and high, the oil viscosity drops dramatically and the turbine can work properly. This flow meter is powered from a loop from 24 V power supply. Electromagnetic sensor generates a pulse signal which is later converted to 4-20 mA signal.

Temperatures of flue gas were measured in four distinct points. The first one was located in the main stream right above the burner. In this case a corundum coated S-type fireproof thermocouple was used to ensure the stable measurement in aggressive environment. The second and third point of measurement was between inner and outer coil and near the boiler wall, respectively. In both cases a K-type thermocouple was used. The last measurement point was located inside the stack and the K-type thermocouple was a part of gas analyzer sensor. A measurement set for balancing the coil type biomass boiler unit is presented in Fig. 2.

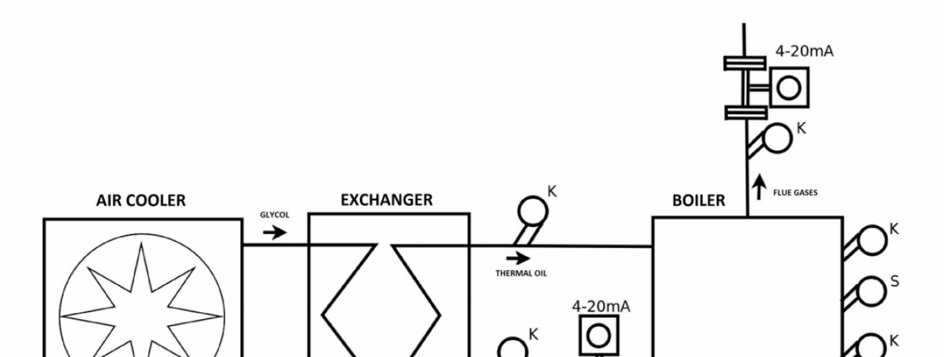

Figure 2. Scheme of measurement set for balancing coil type biomass boiler unit: S, K stands for thermocouple type, and 4-20mA represents signal type from three flow meters.

4 Results

Experimental research conducted on helical coil biomass boiler with oil as a heating fluid a further was development of the previous version referred to [3]. The original air fan was replaced with a stronger, more efficient unit to overcome high choking appearing at large fuel flow rates. Furthermore, both coils had been cleaned prior to the experiment. It was noticed that large amounts of ash and other particles tend to adhere to the coil surface, thereby reducing its thermal efficiency [4]. Surface cleaning issue is yet to be resolved.

In the research the wooden pellets were used as a fuel. This particular fuel is characterized by 5% moisture content and lower heating value of 16.5 MJ/kg. Moisture content was measured on the drying scale and the heating value was obtained using the calorimeter. The chemical composition of dry fuel was examined by means of CHNS-analyzer to determine excess air number. Figure 3 shows the Sankey diagram for the maximum efficiency conditions. Some exemplary plots of oil inlet/outlet temperature as well as the dependence of power and efficiency of the boiler against air excess number for three separate oil flow rates and fixed fuel flow rate have been presented in Figs. 4 and 5.

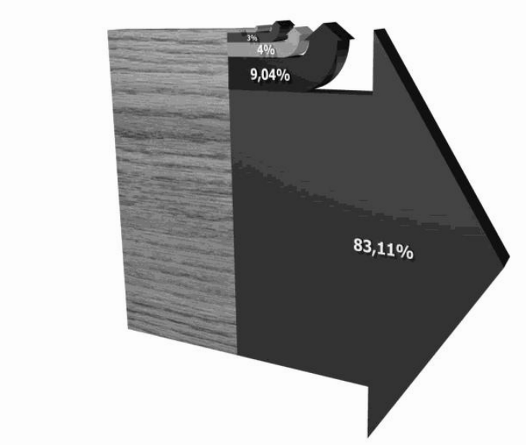

Figure 3. Sankey diagram for maximum efficiency point. From the top: imperfect combustion loss (0.86%), radiation and convection loss (3%), unburned fuel loss (4%), flue gas loss (9.04%).

Considering the fact that the biomass reservoir is fixed to the burner, it was impossible to accurately determine the exact amount of fuel delivered to the combustion chamber, therefore the efficiency of the boiler was calculated indirectly, based on the flue gas composition and temperatures [5]. Note that all of the values in square brackets are volume concentrations [% vol.].

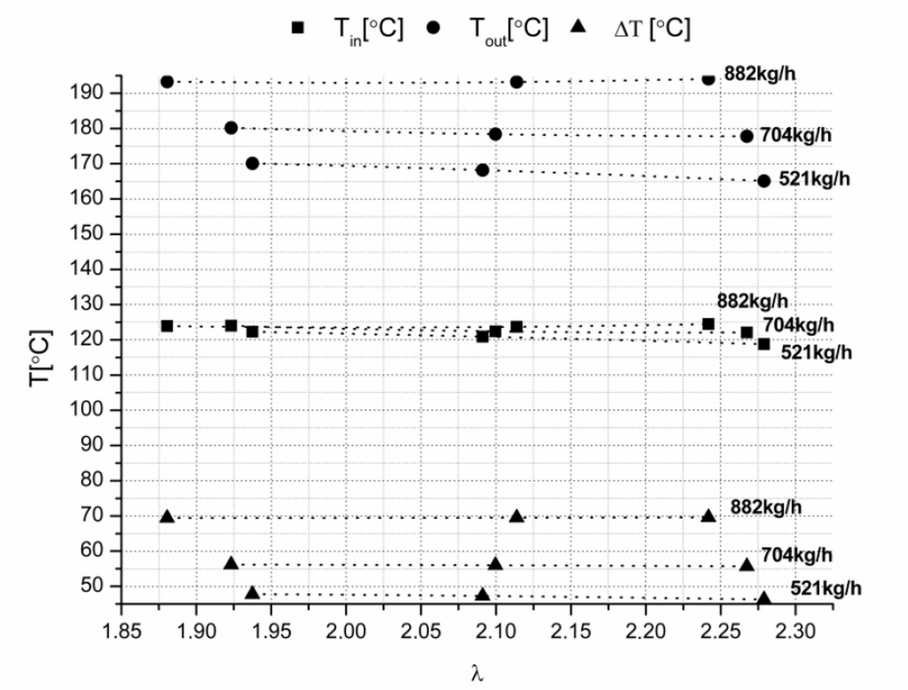

Figure 4. Temperatures of thermal oil on inlet (T_{in}), outlet (T_{out}) and difference between the two versus air excess number (λ) for three oil flow rates and fixed fuel flow rate.

Radiation and convection loss, S_r, was estimated for all of the not insulated surfaces to be approx. 3%. Flue gas loss, S_{fg}, was calculated using formula empirical [6]

$$S_{fg} = \sigma \frac{(T_{gas} - T_{amb}) + 0.59\,[\mathrm{CO}]}{[\mathrm{CO}] + [\mathrm{CO_2}]} \tag{1}$$

where σ is a constant that corresponds to the type of the fuel, its moisture content and amount of CO_2 in flue gas, T_{gas} is the temperature of the flue gas, and T_{amb} is the ambient temperature. For wood with a very low moisture content and concentration of CO_2 in flue gas about 15% coefficient σ equals to 0.75. Furthermore, the average ambient temperature, T_{amb}, was set to -10 °C.

Unburned fuel loss, S_u, was not calculated, but was assumed to be not less than 4%. However, imperfect combustion loss was calculated as [6]

$$S_{im} = \frac{69\,[\mathrm{CO}]}{[\mathrm{CO}] + [\mathrm{CO_2}]}\ . \tag{2}$$

Total heating efficiency of the boiler was determined as the sum of all contributions

$$\eta = 100 - S_r - S_{fg} - S_u - S_{im}\ . \tag{3}$$

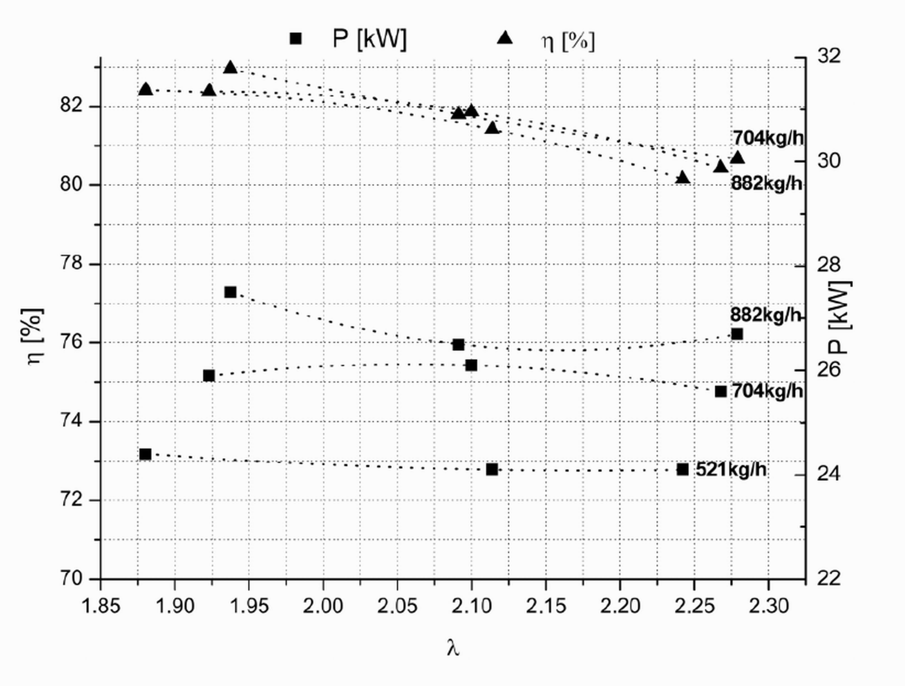

Figure 5. Power (P) and efficiency (η) of the boiler versus air excess number (λ) for three oil flow rates and fixed fuel flow rate.

The amount of power transferred from the hot stream of flue gas to the thermal oil was acquired from both oil flow rate and inlet/outlet temperatures of the media. The specific heat of the oil was calculated for mean value of oil temperature in the exchanger using formula

$$C_p = 3.594T_{mean} + 830.934 , \tag{4}$$

where T_{mean} is the mean temperature of the oil in the coil exchanger.

Using acquired and calculated data plots of power and efficiency of the device in terms of air excess number and thermal oil flow rate were plotted. In Figs. 6 and 7 the dependence of boilers thermal efficiency and dependence of power transferred to the heating agent against air excess number and oil flow rate are presented.

Oxygen, O_2, and carbon dioxide, CO_2, as well as carbon monoxide, CO, are the basic indicators of the combustion quality [7]. Concentration $[O_2]$ and $[CO_2]$ versus air excess number and oil flow rate is shown in Fig. 8, wheares [CO] concentration in terms of air excess number and oil flow rate was presented in Fig. 9.

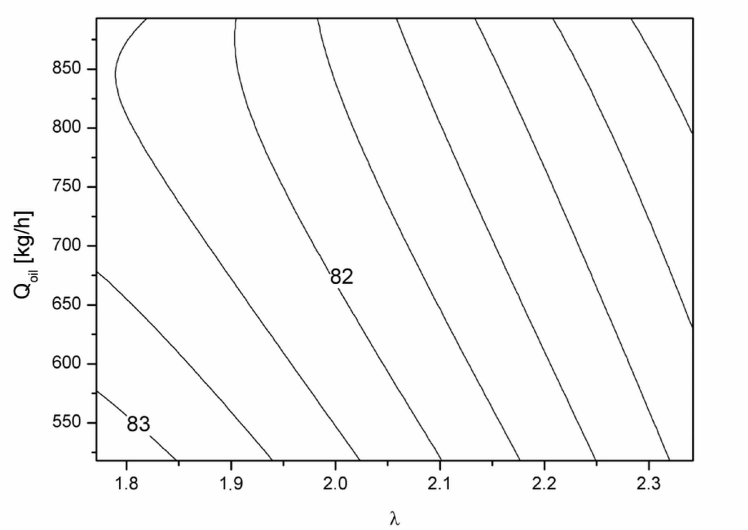

Figure 6. Thermal efficiency of the boiler (η) [%] against air excess number (λ) and oil flow rate (Q_{oil}).

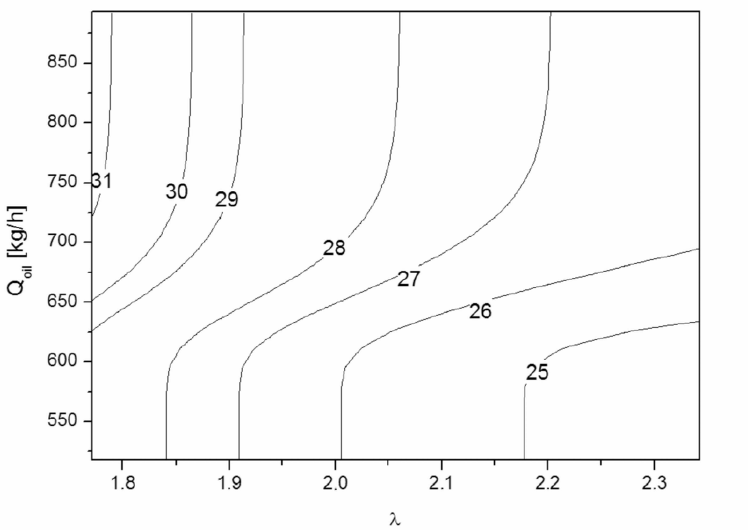

Figure 7. Power [kW] transferred to the thermal oil against air excess number (λ) and oil flow rate (Q_{oil}).

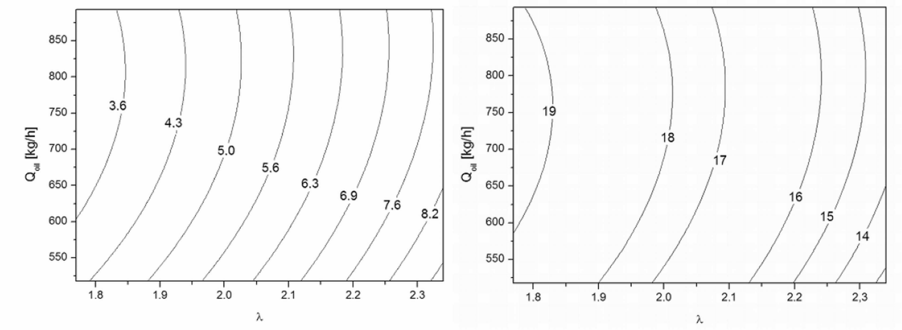

Figure 8. Concentration [% vol.] of oxygen (left) and carbin dioxide (right) versus air excess number (λ) and oil flow rate (Q_{oil}).

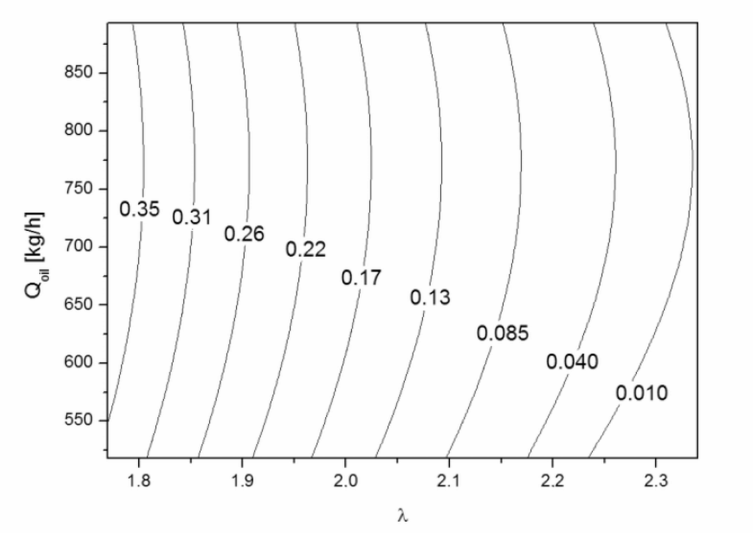

Figure 9. Carbon monoxide concentration [% vol.] versus air excess number (λ) and oil flow rate (Q_{oil}).

5 Summary and conclusions

Considering the fact that the experimental research was conducted in a very narrow range of the air excess number, its influence on combustion efficiency is not major. Calculations show, that the maximum efficiency of the boiler unit is 83% and occurs for low air excess numbers and oil flow rates. Analysis of the heating power of the boiler unit showed a significant dependence on the air excess number, which is understandable considering a relation between the amount of fuel and air. The increase in oil mass flow rate results in increase of power of the boiler unit. By increasing the oil flow rate from 500 to 900 kg/h, the power transferred to the oil rises by 2 kW which stands for 10% of the nominal power of the unit. On the other hand however, the air flow gives a significantly wider power control range (up to 5 kW). The decrease of oil flow rate results in increase in air-based power control range.

The volume concentration of O_2 in flue gas falls between 3.6 and 8.2%, while the optimal concentration of 6% occurs for the air excess number approx. equal to 2. Furthermore, for considered in the research oil flow rate range, the concentration of O_2 decreases with the mass flow of thermal oil. The flue gas contains CO_2 in the range from 13 to 19% and the concentration of carbon dioxide for $\lambda \approx 2$ rests between 17 and 18%. As shown in Fig. 9, the concentration of CO significantly drops after exceeding certain boundary value of $\lambda \approx 2$. For higher values of air excess numbers, the concentration of CO becomes insignificantly low thereby reducing heat losses. It is clear, that the value of $\lambda \approx 2$ is a basic condition for efficient combustion of this kind of fuel.

During the experiment, the researchers came across two significant technical problems. The first one is connected with the retort-type biomass burner. While the biomass is transported to the burner it absorbs certain amount of heat, dries up and changes itsstructure. During the transport process, the biomass trapped inside the feeding screw shell heats up and low temperature pyrolysis takes place, producing large amounts of tar and blocking the device. To eliminate this issue, a gravitational feeding biomass burner, in which the flame and the biomass reservoir are separated, was chosen for further research. The second issue involves the coil exchanger. During the experiment, a thick layer of ashes and other particles attached itself to the heat exchanger surface reducing its heat transfer efficiency. Further improvements will have to include the exchanger surface cleaning system for example integrated with the flue gas swirler.

Acknowledgments The investigations presented in this paper have been carry out within a National Project POIG.01.01.02-00-016/08 “Model agroenergy complexes as an example of distributed cogeneration based on a local renewable energy sources”.

Apart from the efforts of the authors, the success of any project depends largely on the encouragement and guidelines of many others. We take this opportunity to express our gratitude to the man who has been instrumental in the successful completion of this project. We would like to show our greatest appreciation to Mr. T. Kamiński, MSc. Without his encouragement and guidance this project would not have materialized. The authors are grateful for his constant support and help.

Received 6 March 2013

References

[1] Kardaś D., Polesek-Karczewska S.: *Establishing assumptions and calculations of biomass and biogas fired furnace tube and smoke tube bilers with oil heating agent.* Rep. IF-FM PAS 7591/07, Gdansk 2007 (in Polish).

[2] Ronewicz K., Turzyński T., Kardaś D., Wardach-Święcicka I., Kulikowicz W.: *Development of guidelines for the design of the furnace and the fuel supply to the thermal oil boiler.* Rep. IF-FM PAS 623/2012, Gdańsk 2012 (in Polish).

[3] Kamiński T., Kardaś D.: *Measurement characteristics of a thermal oil biomass boiler in ORC installation.* Arch. Energ. **XLII**(2012), 2, 49–58 (in Polish).

[4] Nagórski Z., Sobociński R.*: Selected Aspects of Technical Thermodynamics.* Warsaw Technical University Publishing House, Warsaw 2000.

[5] Piotrowski W., Rokicki H., Szałucki R.: *Steam generators. Examples of calculations.* Gdansk Technical University Publishing House, Gdańsk 1984 (in Polish).

[6] Mieszkowski M. (Ed.): *Thermal and Energy Measurements.* II edn. NT, Warsaw 1985 (in Polish).

[7] Wróblewski T., Pepłowski A., Górecki H.: *Boilers.* NT, Warsaw 1960 (in Polish).