PROTOTYPE OF THE DOMESTIC CHP ORC SYSTEM: CONSTRUCTION AND EXPERIMENTAL RESEARCH

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ABSTRACT

This paper presents the prototype of micro CHP ORC power plant, elaborated at the Institute of Fluid-Flow Machinery PASci, Gdansk. The design and investigation of the micro CHP ORC (Organic Rankine Cycle) system are discussed. The source of heat is a newly-developed boiler, adapted to burn biomass. Electricity was generated thanks to a specially designed vapour microturbine. The gas bearings which are supplied by a working medium allow the turbogenerator to have a space-saving, hermetical structure. In the article the selected results of experimental studies are discussed. Thermal and flow characteristics were presented, allowing the evaluation of operating efficiency of boiler, heat exchangers, pumps, valves and other subassemblies. In addition, the test results concerning turbogenerator were attached, including its power output for various cycle parameters. The results obtained showed that the developed prototype operates in accordance with design solutions and the boiler's thermal output of 25 kW makes it possible to generate above 2 kW of electric power. The results also confirmed that this system may be used to develop a commercial version for this type of device.

1. INTRODUCTION

The micro CHP power plant with ORC is nowadays one of the fastest growing technologies, when it comes to combined generation of heat and power on a small scale. The popularity of this technology is based on a very broad scope of applications (Kicinski, 2013), since it can produce electricity irrespective of the type of heat source used. Depending on local energy resources, the ORC system can cooperate with different types of boilers, geothermic, waste heat and even as a kind of superstructure in bigger energy systems. Numerous research centers worldwide are being involved in the development of such high quality components or entire energy systems. The majority of scientific publications present the studies conducted on research installations under laboratory conditions. In the power range reaching several kW, commercially available solutions have hardly existed up to now.

The ongoing work is mainly intended to develop this ORC technology to the commercial level. An implementation of the technology is related with the need to overcome technical and economical barriers. The major technical problem is the construction of the expander. It is possible to apply solutions of various type in this power range, including screw expanders, scroll expanders, vane expanders or turbine expanders (steam micro-turbines). A systematic literature review on different types of expanders, mainly units up to 10 kWel, which are currently under development by industrial and research centers was presented in the article Qiu et al. (2011). None of the expanders reached series production status. According to Qiu et al. (2011), screw and blade expanders have the greatest number of advantages in the power range up to 10 kWel. The subject matter of the study on different types of expanders is the improvement in efficiency. The works are in progress in this scope either through experimental studies (Wang et al., 2011, Declaye et al., 2013, Hsu et al., 2014) or numerical calculations (Clemante et al., 2012, Fiaschi et al., 2012, Klonowicz et al., 2014, Cordiner and Mulone, 2014). Research on expanders is also underway at the IMP PAN, in Gdansk. The last investigation showed, that the turbine expanders are the most attractive solutions in a domestic environment (Kaczmarczyk et al., 2013, Kicinski and Zywica, 2014). They do not require an oil lubrication or dynamic seals and are very quiet, compared with other expanders. Higher rotational speed entails a reduction in the overall size of a turbine, so microturbines possess compact dimensions and low weight. The only rotating element is the rotor with a turbine and a generator, which does not wear out during use if bearing system had been properly designed (Kozanecki et al., 2014, Kicinski and Zywica, 2012). They also allow for the achievement of satisfactory level of flow efficiency reaching 80% (Kosowski and Stepien, 2012).

Only very few small ORC systems, among the ones found in the literature, are based on steam micro-turbines. The main reason for this is the lack of ready-made commercially available solutions and the difficulties concerning the design and precise workmanship of micro-turbine elements. The example of such an installation was discussed in publication of Borsukiewicz-Gozdur (2013), but its slow-speed turbine generator (with the nominal power of 9 kWel) was not intended for individual houses and was designed to make use of geothermal sources. The micro CHP biomass-fuelled systems review which may be used, among others, in a domestic environment was presented by Dong at al. (2009). The article also discusses the disadvantages and advantages of different technologies, it also emphasizes a great deal of potential for growth as far as cogeneration on a small scale is concerned. Experimental studies of biomass-fired ORC system are also described in the publications of Qiu at al. (2012) and Liu at al. (2010). Barberi et al. (2012) showed various CHP technologies adapted to domestic environment, taking into account different possible thermal energy sources such as combustion engines, Stirling engines, gas micro-turbines, ORC and thermophotovoltaic systems. Examples of systems for combined heat and electricity generation, which are still at the research stage, were also presented in other articles, e.g. (Pei et al., 2011, Minea, 2014). The article (Pei et al., 2011) shows in detail the research on the system with a steam micro-turbine integrated with outer gear and electricity generator. Literature concerning small ORC systems also pays much attention to modelling of such systems (Liu et al., 2011, Bouvenot et al., 2014).

The prototype of the CHP domestic energy system with ORC, which was developed at The Institute of Fluid-Flow Machinery (IMP PAN) in Gdansk, will be presented in the further part of the article. The fuel for the energy system is a biomass in the form of pellets. The electricity is produced using a high-speed oil-free steam micro-turbine. The energy system dimensions allow for its installation in houses. It is the first CHP energy system of that type in the country (and probably in this part of Europe). The prototype start-up took place in April 2014. Since then different types of experimental studies have been carried out aiming at the identification of characteristics of built device and its optimization.

2. THERMODYNAMIC CYCLE AND SYSTEM'S COMPONENTS

The prototype of the CHP domestic energy system with ORC was created within the framework of the research project co-financed by the European Union. The main objective of the project was to develop energy technologies enabling better use of renewable energy sources. This is why the ORC system which produces the electricity was integrated with biomass-fired boiler. Fuels of this type are easily accessible source of renewable energy and its quantity only slightly depends on weather conditions. Besides, biomass is one of the most popular fuels used for heating of family houses, especially in rural areas.

In the framework of prior design assumptions, demand for heating and for electricity was estimated in an average single-family house. On this basis, it was assumed that maximum capacities of the CHP system should be at level: approx. 25 kW of thermal power and approx. 2.5 kW of electric power. Under these assumptions it was possible to use the expanders of different types. On account of the highest potential for further development as well as operational aspects it was decided to apply the oil-free steam micro-turbine. Machines of this type, in the case of small ORC systems, have several advantages, the most important being high efficiency, no wear parts, hermetic housing and low noise (Kaczmarczyk et al., 2013, Kicinski and Zywica, 2014, Kozanecki et al., 2014). Small dimensions enable to develop compact structure for the entire device which is essential for the use of ORC system in a domestic environment.

After analyses and comparisons, mixture of substances under a trade name HFE-7100 was selected as the working medium (Mikielewicz et al., 2013a). This medium is a modern solvent, and is odourless and non-flammable. Its boiling point at atmospheric pressure is only 61°C.The thermodynamic cycle of the CHP system for the HFE-7100 was designed taking into account several criteria, such as: high efficiency of designed steam micro-turbine, purchase price of other components, net maximum electrical capacity, and availability of control and measurement apparatus in the market. The simplified diagram of the energy system is presented in Fig. 1. A characteristic feature of the cycle was the use of regenerative heat exchanger, which guarantees fairly higher efficiency of the cycle for the selected working medium. Temperature - entropy graph (T-s) for the chosen thermodynamic cycle is showed in Fig. 1. Theoretical energy generation efficiency, according to this cycle, was around 13 % at theoretical net electrical capacity of 2.7 kW. These results conformed (with a certain “safety margin”) with the original design intent.

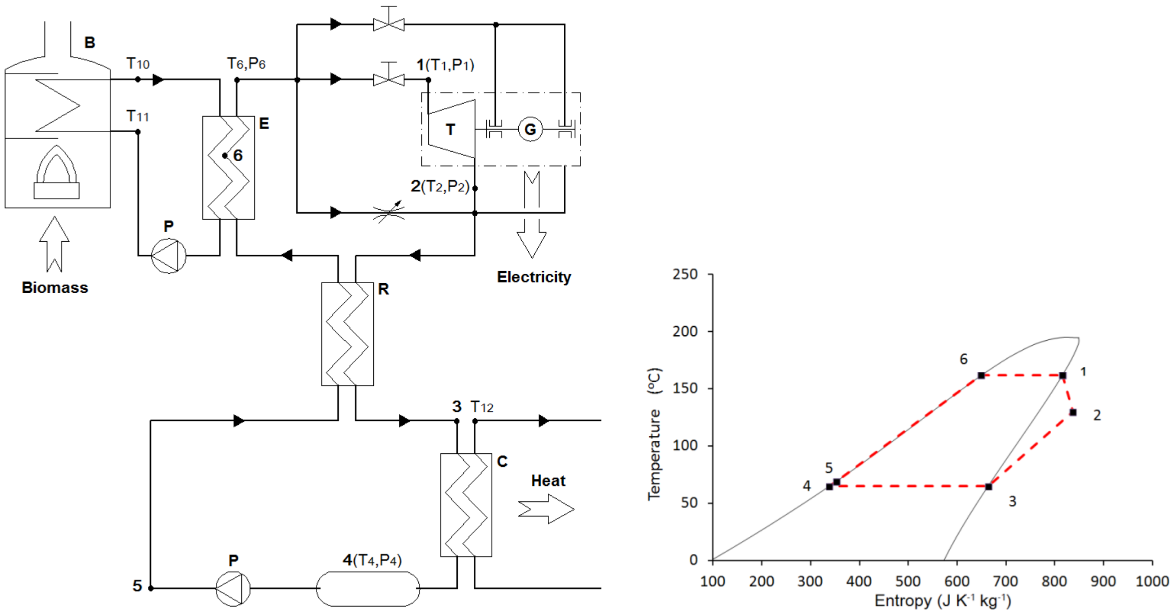

Figure 1: Diagram of the CHP ORC system with a biomass-fired boiler (B – boiler, P – pump, T – turbine, G – generator, E – evaporator, R – regenerator, C – condenser) and theoretical temperature-entropy graph for the ORC system with HFE-7100

On the basis of the characteristics of energy system cycle the selection criteria for all components were elaborated. Then the components were subject to theoretical analyses, design works and laboratory testing. The research was carried out in the laboratory specifically prepared for these tasks. Finally, the best constructional solutions have been selected to guarantee reliable operation and high efficiency of the entire machine. Specification of the basic parameters of the main components in the energy system is shown in Table 1.

Table 1: Basic parameters of the main components in the CHP ORC energy system.

Components	**Basic properties**
Boiler (biomass-fired)	Heat power (continuous) ~ 28 kW
Steam microturbine	Rated power – 2.7 kW (at 24 krpm)
Evaporator	Heat load – 25 kW
Regenerator	Heat load – 22.5 kW
Condenser	Heat load – 6.6 kW
Circulating pump	Nominal pressure difference – 10 bar Nominal capacity – 7.6 lpm

The listed components have successfully undergone experimental tests with the working medium in conditions close to target conditions. It has resulted in several innovative, alternative solutions of boilers (Kardas et al., 2014), circulating pumps (Kaniecki et al., 2013), heat exchangers (Mikielewicz et al., 2013b) and steam micro-turbines (Kicinski and Zywica, 2013, Kozanecki et al., 2014, Stepien, 2013) while working on the components at the IMP PAN. When selecting components, a high level of durability and reliability as well as relatively low price were the important criteria, in addition to capacity demand and efficiency. The applied steam micro-turbine has gas bearings lubricated with steam of low-boiling medium, which allowed the use of hermetic casing. A high-speed generator with rare earth magnets was placed inside the casing, between the bearings. It is a four-stage radial turbine (two centripetal stages and two centrifugal stages). The applied micro-turbine should reach a flow efficiency up to 75% according to the design calculations. The visual appearance of the turbo-generator mounted on the frame of the micro power plant was presented in Fig. 2.

Figure 2: Photo of turbo-generator mounted on the frame of the micro power plant

3. DESIGNING AND BUILDING OF THE PROTOTYPE

The construction solution of the energy system was developed in the form of 3-dimensional, parametric CAD model, on the basis of the design assumptions and selected components. Then, after the preparation of the 2-dimensional technical documentation, the building of energy system at the laboratory of the IMP PAN commenced. The energy system installation together with the supporting structure and an automatic control and energy condition system was named “CHP module”. This module, during normal operation, allows generating electricity after being connected to any source of heat energy, in this case the multi-fuel boiler with thermal oil circulation. The CHP module cooperating with a boiler form a complete CHP ORC energy system, which allows to convert the chemical energy of fuel into thermal energy and electric power.
The main principles that have guided the process of design are listed below:

- logical grouping of prototype components around the biggest component – regenerative heat exchanger,
- arrangement of energy system components towards each other in such a way as to minimize length of the pipelines and to reduce the area occupied by them,
- realization of the following rule: hot vapour at the top, cold liquid at the bottom (micro-turbine - on the highest level, circulating pump - on the lowest level),
- the use of pipelines with diameters not less than nominal diameters of connecting components,
- the use of modular tank for the working medium, enabling the adjustment of the volume of the liquid in front of the pump,
- minimizing the number of angled connections and highly varying diameters of pipelines (trying to reduce pressure losses and drops),
- the use of flexible elements between joined components (compensation of thermal elongations, reducing the transmission of vibrations),
- replacing temporary fastenings by welded joints (improving the leaktightness of the installation) so long as maintaining the dismantling possibilities for any component,

- the use of standard joints and materials that are commonly sold on the market (the ease of rebuilding and repair),
- arrangement of components that support good air circulation, cooling the pump motors and automatics elements (air cooling from bottom to top),
- planning of so-called “transparency side”, on that side the control box was mounted and all screens, being a part of adjustment and measuring equipment which are visible there,
- the use of additional connections enabling easy serviceability of the system (e.g. filling, emptying, deaeration of the system).

When designing the energy system all publicly known principles of designing machinery were also used, maintaining relevant industry standards. The result of design works is presented in Fig. 3 in the form of 3D model.

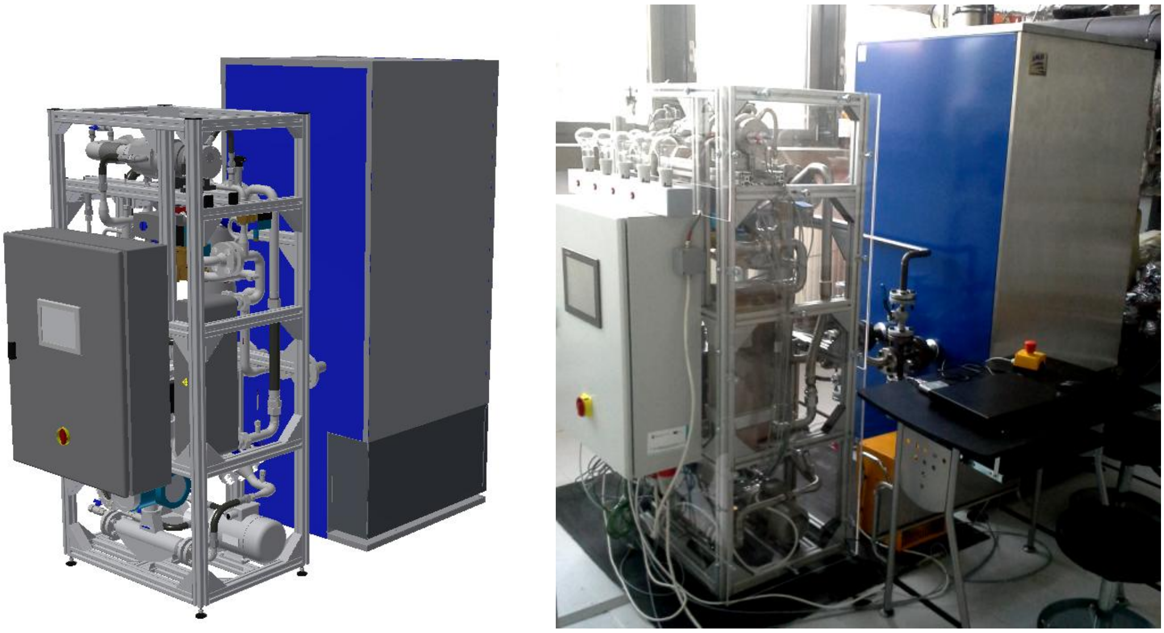

Figure 3: Three-dimensional CAD model and the prototype of the CHP ORC system

The control-measuring system based on universal PLC controller was created, in order to allow monitoring of the functioning of all components and conditioning of the electric energy. In addition, the energy system was fitted with a touch panel mounted on the control cabinet, displaying the most important operational parameters. The automatic control system allows for adjustment of operational parameters of the energy system components and also executive elements of the automatics, such as flow control valves. On the other hand, it also functions as a measurement & control system enabling achieving, visualizing and archiving of measured signals. The photo of the energy system with measurement & control system is showed in Fig. 3.

4. THE RESULTS OF EXPERIMENTAL INVESTIGATION

Experimental investigation of micro CHP ORC plant was made under laboratory conditions. The energy system was equipped with electric energy receivers: electric heater with 5 kW of power capacity, 10 bulbs of 1kW total power capacity. The take-up of heat energy from the condenser took place through the system filled with an aqueous solution of glycol fitted with outdoor dry air coolers. Combustion gases from the boiler were discharged through a stainless steel stack. During start-up tests the boiler was fired with biomass in the form of pellets, which was delivered to the furnace using an automatic feeding screw.

The aim of start-up tests was primarily to verify the correct functioning of all main components cooperating with each other in the ORC system and also checking whether the protective equipment and automatic control system are operating well (Kicinski et al., 2014). The start-up tests began before completing thermal insulation of the installation and some components (such as heat exchangers). It greatly facilitated searching for possible leakage points and allowed faster removal of leaks. It was connected with high heat losses that prevented the energy system from obtaining nominal operating parameters. Therefore, the effort was not aimed at achieving pre-determined micro-turbo-generator parameters during the first start-up attempts, but they were carried out only to check whether the steam micro-turbine functions properly. Preliminary tests lasted several hours in total. Selected measurement results were presented in the figures below.

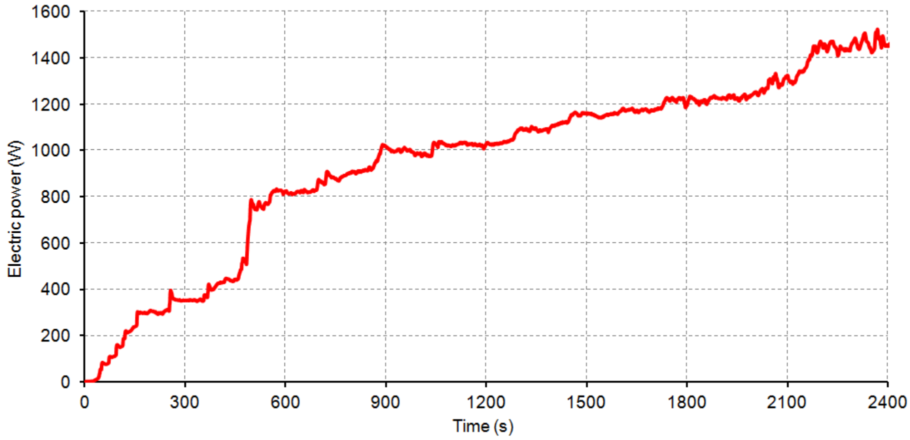

Figure 4: Electric power of the turbo-generator during preliminary tests of the CHP ORC energy system.

The amount of electricity generated during the 40 minutes start-up period is presented in Fig. 4. By adaptive control of the circuits the stable operation and a gradual increase in power output were obtained. The maximum electrical power was above 1500 W at the output of the electric energy conditioning system. The micro-turbine's shaft was operating with rotational speed around 18 000 rpm and around 6 000 rpm was still needed to reach nominal speed.

The temperatures of all the mediums that are present in the installations of the energy system measured during 2400 seconds are shown in Figures 5 and 6. The values of the temperature of low-boiling medium at different points of the ORC system are presented in Figure 5a. The temperatures after the evaporator and before the micro-turbine remained at similar levels and this was an indication of low heat losses. On the characteristics below, the gradual increase in temperature of the low-boiling medium before the pump may be also observed. That temperature was above 50 °C towards the end of the period concerned. The difference in temperature between the inlet and outlet of the micro-turbine was in the range of 10 to 22 °C. The temperature of HFE-7100 was measured in the tank at the pump inlet. The high degree of supercooling was achieved through the use of advanced cooling system with the fan and water spraying. In the figure 5b there is also a graph representing the absolute pressure of HFE-7100 at selected points in the ORC system. At the beginning of the test a vacuum procedure was done, to remove air from the ORC system. The highest pressure value reaching 11 bar took place directly at the outlet of the evaporator (P6). The pressure before the micro-turbine (P1) continued to increase together with gradual opening of the control valve. It was only marginally less than the pressure after the evaporator when the valve was fully open. The difference was approximately 0.3 bar. The vapour of the low-boiling medium after the micro-turbine, sharply declined its pressure to approx. 3 bar. The biggest pressure drop occurred at the end of measurement session, it was about 7.5 bar.

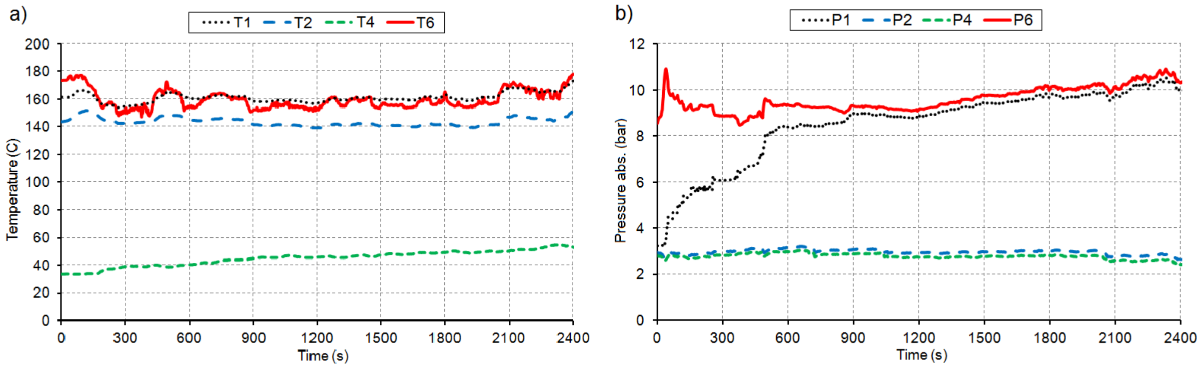

Figure 5: The temperature (a) and absolute pressure (b) of the HFE-7100 during tests performed on the ORC system (T1 – temperature at the inlet of the micro-turbine, T2 – temperature at the outlet of the micro-turbine, T4 – temperature of the medium in the tank at the inlet of the pump, T6 – temperature at the outlet of the evaporator, P1 – pressure at the inlet of the micro-turbine, P2 – pressure at the outlet of the micro-turbine, P4 – pressure in the tank at the inlet of the pump, P6 – pressure at the outlet of the evaporator).

Figure 6a presents the graph of thermal oil temperature in the inlet and outlet of the boiler. The maximum temperature at the evaporator inlet slightly exceeded 200 °C only for a short time and at its outlet amounted to around 150 °C. These parameters were stable over the period considered. A decrease of oil temperature has continued on the level of 50 °C during the tests. Figure 6b presents also the graph which shows the temperature of aqueous solution of glycol used to receive the heat in the condenser. The measurement was performed after the solution had flowed through condenser, therefore, after receiving heat energy from the working medium. At the end of measurements the temperature of the solution of glycol reached up to 70 °C and rose steadily, which was mainly the result of limited capabilities of heat consumption. This problem increased at high air temperature outside the building.

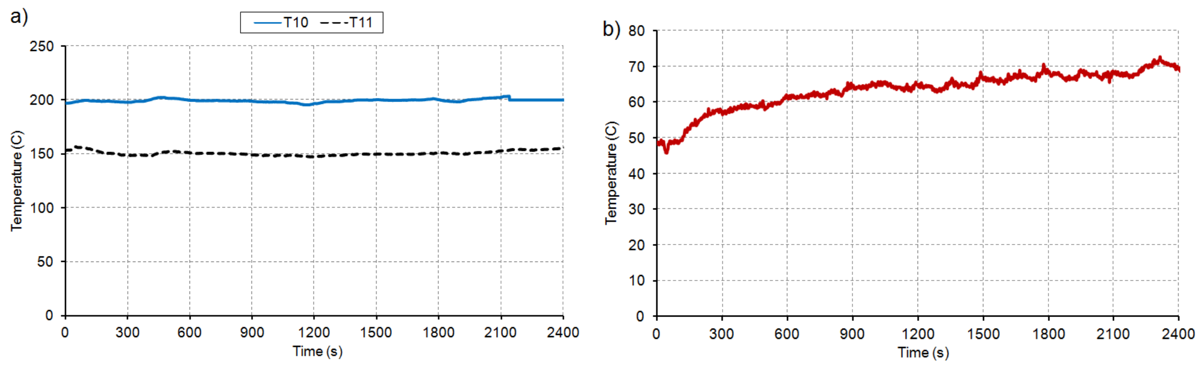

Figure 6: Temperature of the thermal oil (a) and aqueous solution of glycol (b) after the condenser (T12) during tests performed on the ORC system (T10 – temperature at the outlet of the boiler, T11 – temperature at the inlet of the boiler).

An important aspect to the tests performed on the ORC system is the flow rate of working medium. The measured value of flow rate for the low-boiling medium HFE-7100 was up to a maximum of 140 g/s. It constitutes 83 % of the nominal value of flow rate, which is 169 g/s. In terms of flow parameters, their optimal values for the micro-turbine have not been achieved during the tests. Both the level of pressure difference and flow rate was found to be below the design values. The flow rate of the thermal oil used as a heat-carrying agent between the boiler and the evaporator amounted to roughly 20 lpm. This value was close to the nominal value.

5. CONCLUSIONS

The article presents the prototype of the CHP ORC energy system. The preliminary research results were obtained from the tests during which the proper operation of all components in working medium heating and cooling processes was tested, and also from the tests in the operating mode in which the micro-turbine generates electricity. The results confirmed the proper functioning of all components, automatic control system and the system receiving the electricity generated. The electrical power generated by the energy system was around 1.5 kW, because the installation was not yet fully prepared to achieve the nominal power. The turbine operation takes place with lowered pressure and flow rate of the working medium which impedes the performance of the system. The incomplete thermal insulation resulted in pretty high heat losses. In view of the obtained results and the past experiences, it can be said that when the installation is in optimum condition the built ORC energy system will make it possible to generate around 2.5 kW of electric power.

The target group of the developed micro power plant are the inhabitants of single-family houses, who, up to now, have been using biomass or other fuels to heat buildings. The works on the commercial version of the energy system are being planned in the near future. They will be carried out in cooperation with an industrial partner that have appropriate back-up facilities providing technology and marketing support and which already has its own distribution network in the market. It seems that, with the right policy of the country related to the use of renewable energy, the proposed domestic CHP ORC energy system can become a very attractive source of clean energy.

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