THERMOGRAPHIC INVESTIGATION OF THE COGENERATIVE ORC SYSTEM WITH LOW-BOILING MEDIUM

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Summary

The paper presents the results of experimental investigations of the ORC system equipped with the expansion valve simulating microturbine operation. The aim of the research was to verify the correct functioning of the installation components and to access the technical condition of the thermal insulation in the heating and cooling mode with regard to the design assumptions. The research was conducted for different values of medium flow rates. The images were acquired using the thermal imaging camera FLIR E50, which is equipped with a specialized software. On the basis of the experimental results, the heat losses have been estimated, together with the places which were the major source of loss (the so-called thermal bridges). It was shown experimentally that the application of a thermal imaging camera can constitute a simple and fast thermal diagnostics method for installations of this type.

Keywords: Organic Rankine Cycle, low-boiling medium, thermographic.

BADANIA TERMOWIZYJNE UKŁADU KOGENERACYJNEGO ORC Z CZYNNIKIEM NISKOWRZĄCYM

Streszczenie

W pracy przedstawiono wyniki badań eksperymentalnych układu ORC z zaworem rozprężnym symulującym pracę mikroturbiny. Badania miały na celu sprawdzenie poprawności działania podzespołów instalacji oraz ocenę stanu technicznego izolacji termicznej podczas procesów grzania, chłodzenia i regeneracji w stosunku do założeń projektowych. Badania przeprowadzono dla wybranych natężeń przepływów mediów roboczych. W badaniach wykorzystano kamerę termowizyjną FLIR E50 wraz ze specjalistycznym oprogramowaniem. Na podstawie wyników badań oszacowano straty ciepła instalacji oraz określono miejsca, w których występowały największe straty (tzw. mostki termiczne). Wykazano, że zastosowanie kamery termowizyjnej może być szybką i prostą metodą diagnostyki termicznej tego typu instalacji energetycznych.

Słowa kluczowe: obieg organiczny Rankine`a, czynnik niskowrzący, termografia.

1. INTRODUCTION

In the recent years, cogenerative systems allowing for the use of waste heat for electricity production have gained a lot of attention. Especially popular among them are ORC (Organic Rankine Cycle) systems. They use low-temperature heat sources (up to 300^{o}C), either of natural origin (biomass, geothermal, solar power) or in the form of waste heat, for example from post-production processes [1].

The micro ORC system has been designed and constructed at the Szewalski Institute of Fluid-Flow Machinery PAS in Gdańsk. The ORC installation can co-operate with various expansion devices (e.g. vapour turbines and scroll expanders). The multifuel boiler and electric flow heater for thermal oil be used as a heat source.

Example experimental investigations of the ORC system with the microturbine and the expansion valve are provided in references [2, 3].

The ORC installation has a thermal insulation to raise heat efficiency. The amount of heat losses to the environment was estimated using the compact infrared thermal imaging camera. Subsequently, thermal bridges were detected and eliminated.

Thermovision has become widely used in different areas of technology, and can be applicable, inter alia, in biology [4], building industry [5], medicine [6], analyses of thermal processes [7], materials testing [8, 9] and machine diagnostics [10–13]. Thermovisional measurements are commonly used for NDT (non-destructive testing) and they complement other diagnostic tests [14].

2. TEST BENCH

The ORC installation (which is situated in the Micro ORC Power Plant Laboratory) is composed of three basic cycles: a heating cycle, cooling cycle and a working fluid cycle. The ORC test bench is presented in Figure 1.

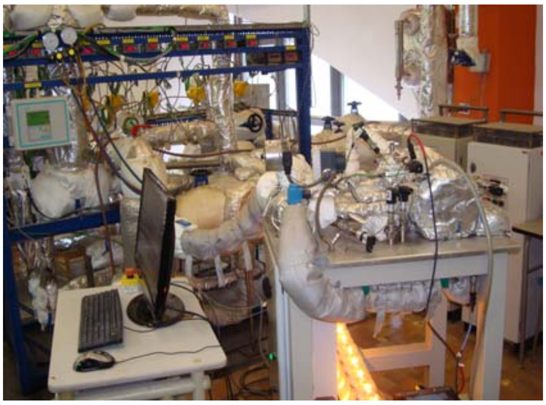

Fig. 1. The ORC system with a microturbine and expansion valve in the test bench

The heating cycle consists of a group of oil pumps and two independent heat sources: a multifuel boiler and a set of two electric thermal oil heaters that can operate independently or in series/in parallel. The ORC installation can operate using an expansion valve (simulating operation of a microturbine), a microturbine or different expanders.

The measurement scheme of the regenerative ORC system with expansion valve and microturbine is presented in Figure 2.

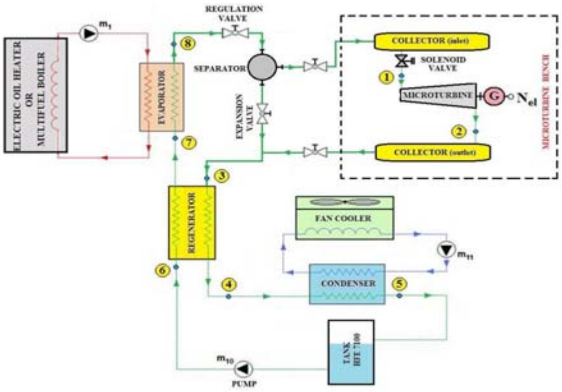

Fig. 2. Measurement scheme of the regenerative ORC system with expansion valve and microturbine

The characteristic points 1 – 8 for the regenerative cycle have been marked. These points were used to determine the changes in thermodynamic state of the working medium in the ORC installation.

The heating cycle has two heat sources. The first one is a prototypical multifuel boiler, alternatively fuelled with biomass, town gas, or gas obtained by gasification of biomass. Another heat source is also a prototypical electric flow heater for thermal oil. The prototypical electric flow heater for thermal oil consists of two modules. Both modules can operate independently or in series and are designed to heat non-conductive fluids (thermal oil) to the temperature of about 250^{o}C with low heat flux density (below 3 W/cm^2) and the power of 2x24 kW$_e$. The boiler is equipped with a coil heat exchanger for double exhaust gas circulation which increases its effectiveness. The maximal boiler power during biomass combustion (pellets of about 5 mm diameter) is about 30 kW$_{th}$.

2.1. Measurement process

As a result of heating the working media (thermal oil, HFE7100 and glycol), the changes in the flow rate take place, being caused by the change of physicochemical parameters (i.e. density, viscosity). The definition of steady state was introduced. Steady state denotes the state in which the flow rate change of the working media does not exceed 1% of the maximum flow rate for 15 min. The acceptable maximal (1%) average flow rates are: for the thermal oil – 0.004 kg/s, for the HFE7100 – 0.002 kg/s and for the glycol – 0.005 kg/s. Additionally, the change of average pressure in the steady state should not exceed 12 kPa (i.e. 1% of the maximum pressure value) for 15 min., and the changes in temperature values should not exceed 1^{o}C. Thus, the steady state is when the average change values of pressure, flow rate and temperature do not exceed 1% of the maximum value for 15 min.

The surface temperature measurement of the insulated components of the ORC installation was carried out with infrared thermal imaging camera FLIR E50, which is equipped with FLIR Tools software. Black tape was glued on the surfaces of tested elements (at the measuring points) and the temperature measurements were conducted in the steady state with the thermal imaging camera. As soon as the measurement data were processed, the photo and the thermal image of tested component were obtained. The abovementioned thermal imaging camera enables measuring surface temperature in two ranges: -20^{o}C to 120^{o}C and 0^{o}C to 650^{o}C. Thermal sensitivity NETD of the E50 camera is below 0.05^{o}C at 30^{o}C. The accuracy of measurement is ± 2^{o}C (for the ambient temperature in the range: 10^{o}C to 35^{o}C).

3. EXPERIMENTAL RESULTS

In the first place, the experimental results of the heat exchangers installed on the ORC test bench were presented, such as evaporator, condenser and heat regenerator characteristics.

Figure 3 presents the temperatures of the working media (HFE7100 and thermal oil) in the evaporator.

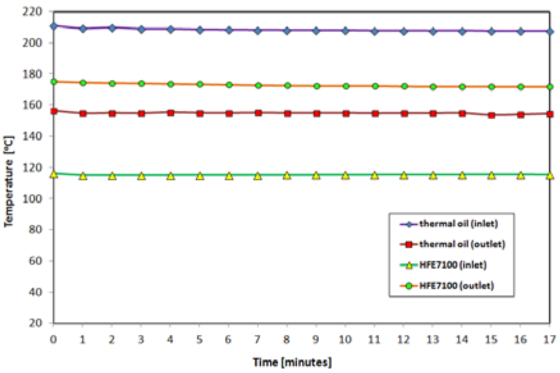

Fig. 3. The temperatures of working medium in the evaporator vs. time

The average temperature of thermal oil at the evaporator inlet was 210°C and at outlet was 155°C. The average temperature HFE7100 at the evaporator inlet was 115°C and at outlet was 165°C.

Figure 4 shows the temperatures of the working medium HFE7100 in the regenerator.

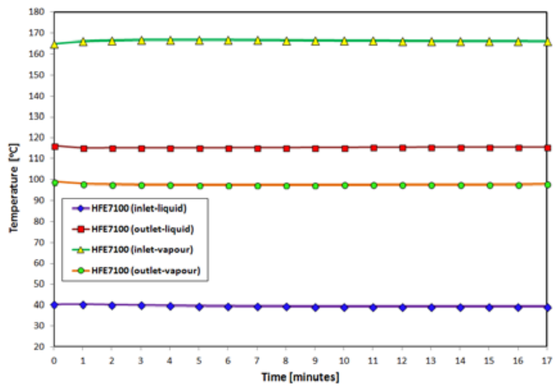

Fig. 4. The temperatures of the HFE7100 in the regenerator vs. time

The average temperature HFE7100 at the vapour side was 165°C and 95°C at the inlet and outlet, respectively. The average temperature HFE7100 at the liquid side was 40°C and 115°C at the regenerator inlet and outlet, respectively.

Figure 5 presents the temperatures of the HFE7100 and glycol in the condenser.

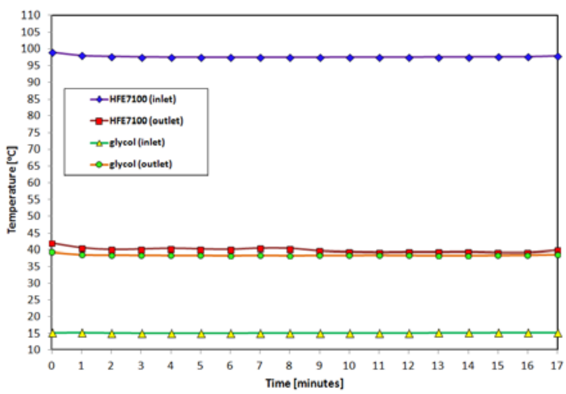

Fig. 5. The temperatures of the HFE7100 and glycol in the condenser vs. time

The average temperature of the glycol was 15°C at the condenser inlet and 40°C at outlet. The average temperature of the HFE7100 was 97°C and 42°C at the condenser inlet and outlet, respectively.

The next stage of tests were the thermovision investigations. Figure 6 shows the photo of the test object and Figure 7 presents of its thermal image (pump operating with HFE7100).

Fig. 6. The photo of the pump operating with the HFE7100

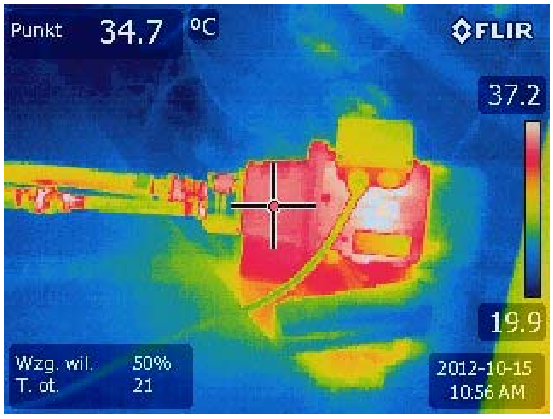

Fig. 7. The thermal image of the pump operating with the HFE7100

The average surface temperature of the pump was 35°C. Figures 8 and 9 presents the photo and thermal image of the expansion valve in the ORC system.

Fig. 8. The photo of the expansion valve

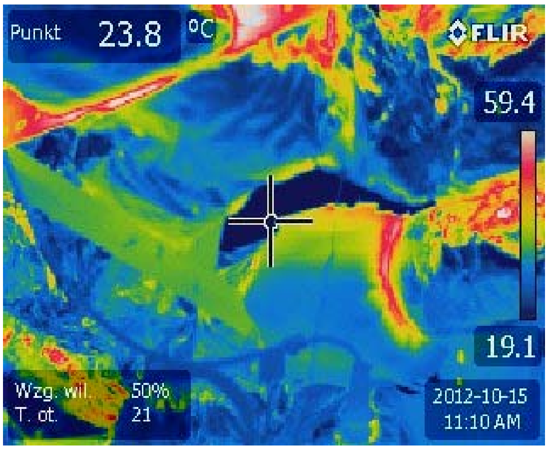

Fig. 9. The thermal image of the expansion valve

The average temperature surface of the expansion valve was 24°C. The photo of plate heat exchanger (evaporator) is shown in Figure 10 and Figure 11 present its thermal image.

Fig. 10. The photo of the tested evaporator

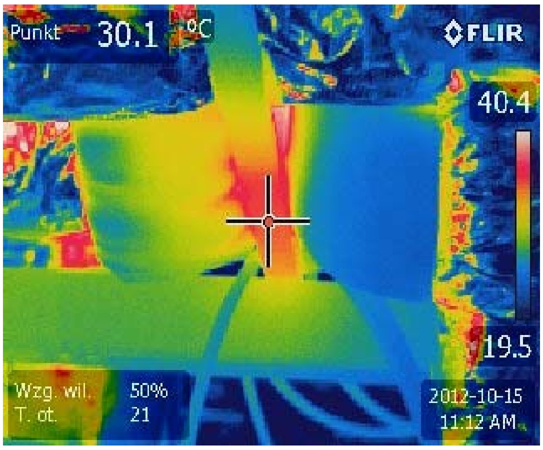

Fig. 11. The thermal image of the evaporator

The average surface temperature of the evaporator was 30°C. Figure 12 presents the picture of the condenser (plate type heat exchanger) and Figure 13 provides the thermal image obtained during the research on the regenerative ORC system.

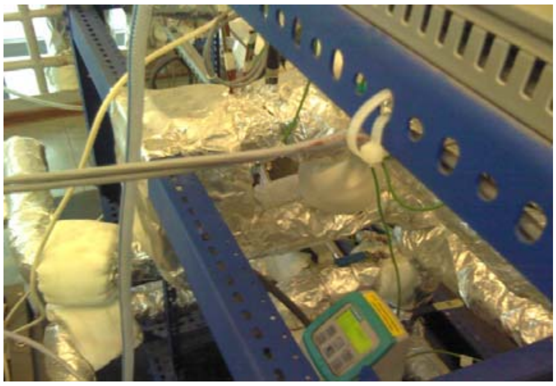

Fig. 12. The photo of the tested condenser

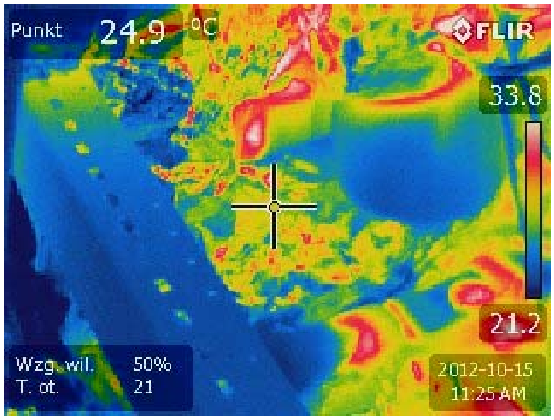

Fig. 13. The thermal image of the condenser

Figure 13 shows that the average temperature surface of the condenser was around 25°C.

The regenerator is shown in Figure14. Figure 15 contains its thermal image obtained during the research on the ORC system.

Fig. 14. The picture of the regenerator

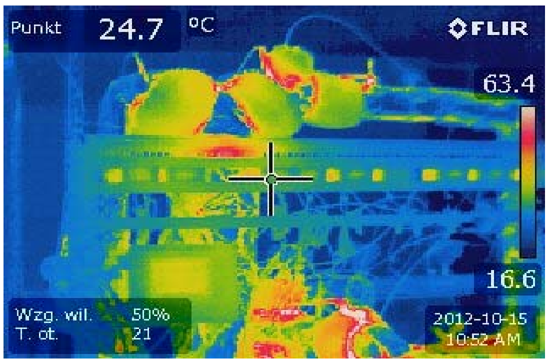

Fig. 15. The thermal image of the regenerator

The average temperature of the regenerator surface was about 25°C.

The picture of pipeline from the evaporator was presented in Figure 16, whereas its thermal image was shown in Figure 17.

Fig. 16. The picture of pipeline from the evaporator

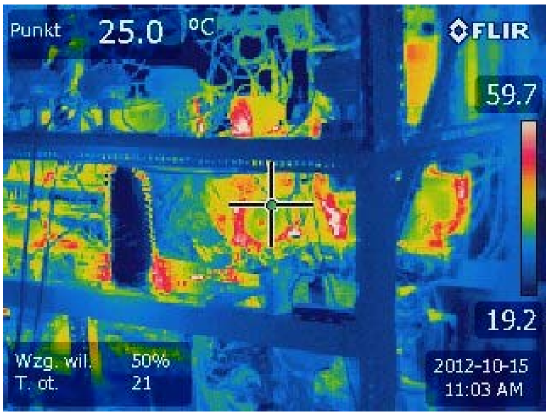

Figure. 17. The thermal image of pipeline from the evaporator

According to the measurements, the average temperature surface of pipeline from the evaporator was 25°C.

The picture of the droplet separator for the HFE7100 vapour is presented in Figure 18 and its thermal image can be seen on Figure 19.

Fig. 18. The droplet separator for the HFE7100

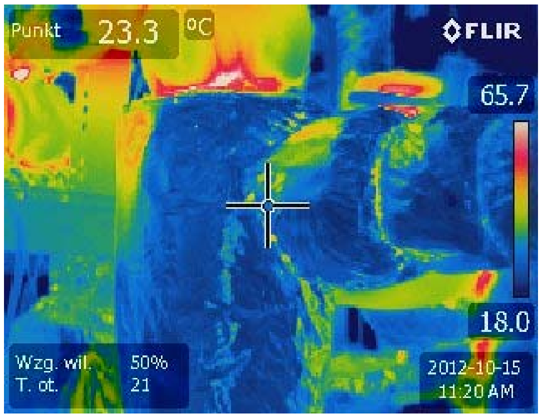

Fig. 19. The thermal image of the droplet separator

The average temperature of the droplet separator surface was 23°C.

The average temperatures measured in the ORC system with sensors (K-type thermocouple) and with infrared camera is shown in the Figure 20. The values in the diagram, shown in red, refer to the temperatures of the working media inside a pipeline whereas the values in blue refer to the surface temperatures of the insulation material.

The heat losses in the ORC test bench result from the heat exchange between the installation and its environment on of thermal radiation and convection. On the basis of the Stefan-Boltzmann Law, the heat losses were evaluated. The equation of the following form was used:

$$Q = \varepsilon \cdot \sigma \cdot A_s \cdot \left(T_s^4 - T_a^4\right) \text{ [W]} \qquad (1)$$

where:

ε – emissivity coefficient [-];

σ – Boltzmann constant ($5.67 \cdot 10^{-8} \left[\frac{W}{m^2 K^4}\right]$);

A_s – heat transfer surface area [m^2];

T_s – surface temperature [K];

T_a – ambient temperature [K].

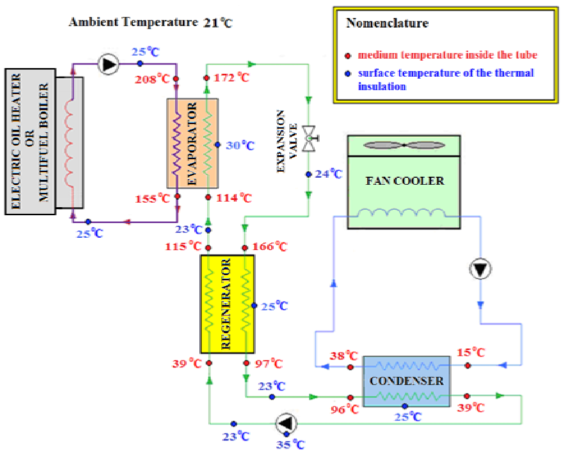

Fig. 20. Scheme of the ORC installation with provided temperature values of the working media

inside a pipeline, and on the surface of the thermal insulation

The emissivity coefficient surface ε assumed equal 1. Once the heat transfer surface area A_s have been calculated and entered in the equation (1), the heat losses can be calculated for the evaporator, regenerator and condenser. The calculated values are as follows:

- evaporator $Q_E = 382\,W$;
- regenerator $Q_R = 616\,W$;
- condenser $Q_C = 142\,W$.

The total heat losses for all heat exchangers (evaporator, regenerator, condenser), denoted by Q_{HE} equal to:

$$Q_{HE} = Q_E + Q_R + Q_C = 1140\,W \qquad (2)$$

In addition to the heat losses in the heat exchangers (Q_{HE}), the heat losses (denoted by Q_P) occurring in the ORC installation (losses in a pipeline) should also be taken into account. It was evaluated on the basis of the equation (1). The heat losses through in the pipelines totalled:

$$Q_P = 2761\,W$$

Therefore, the total heat losses (Q_{ORC}) in the ORC test bench can be calculated as follows:

$$Q_{ORC} = Q_{HE} + Q_P = 3900\,W \qquad (3)$$

The heat losses, before installing extra thermal insulation were:

$$Q_{HE} = 1490\,W$$

On the basis of the results obtained during the tests on the regenerative ORC test bench, the heat balance of heat exchangers have been elaborated. The calculation for fluid-side heat exchangers (thermal oil, glycol, HFE7100) using the following equation:

$$Q = \dot{m} \cdot c_p \cdot \Delta T\ [W] \qquad (4)$$

where:

$\dot{m}$ – flow rate HFE7100 [kg/s];

c_p – specific heat of HFE7100 [J/kg K];

ΔT – temperature difference between the inlet and outlet working medium in a heat exchanger [K].

When calculating the balance, for the working medium (HFE7100) in vapour form the following equation was used:

$$Q = \dot{m} \cdot \Delta h\ [W] \qquad (5)$$

where,

Δh – difference specific enthalpy of a working fluid [J/kg]

The designations of heat flow directions and heat losses in ORC system were shown in Figure 21.

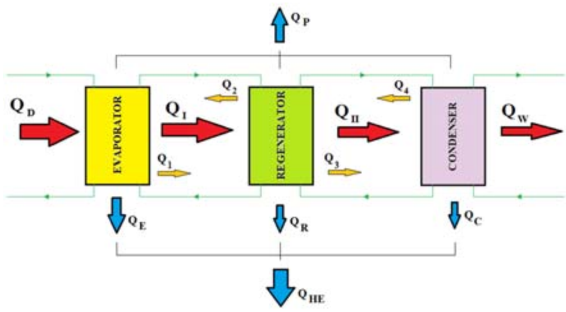

Fig. 21. The designations of heat flow directions and heat losses in the ORC system

Based on the measurement data as well as the equations (4) and (5) the input/output thermal power calculated for the working media was as follows:

- thermal oil $Q_D = 29630\,W$;
- HFE7100 $Q_1 = 13310\,W$;
- HFE7100 $Q_2 = 15240\,W$;
- HFE7100 $Q_3 = 15830\,W$;
- HFE7100 $Q_4 = 9910\,W$;
- glycol $Q_W = 25680\,W$;

Therefore, the power transferred from the evaporator Q_D = 29630 W to the regenerator Q_I will be equal to:

$$Q_I = Q_1 + Q_2 = 28550\,W \qquad (6)$$

While the power transferred from the regenerator Q_I = 28550 W to the condenser Q_{II} amounted to:

$$Q_{II} = Q_3 + Q_4 = 25740\,W \qquad (7)$$

The power loss calculated for the condenser was $Q_W = 25680\,W$. While the power losses resulting from the energy conversion Q_L were the following:

$$Q_L = Q_D - Q_W = 3950\,W \qquad (8)$$

The estimation of the power loss on the basis of thermovision showed that the cumulative losses in the heat exchangers and in the pipelines amounted to Q_{ORC} = 3900 W. When the same parameter was calculated using the values measured by the sensors, it amounted to Q_L = 3950 W. This means that the heat loss values obtained using two different approaches differ only slightly. The equation (9) shows the difference between them.

$$\Delta Q = Q_L - Q_{ORC} = 50\,W \qquad (9)$$

It can be stated that the heat losses, in relation to the system as a whole, average 13% of the total input heat power. Please note that these heat losses, after the first insulation of the test bench were around 25% of the total input heat power [15].

4. CONCLUSIONS

The use of a thermal imaging camera for the purposes of heat loss analysis in an ORC system ensures fast measurement and the immediate determination of heat losses in an installation. It enables to detect thermal bridges, which is practically unfeasible using classical measurement methods.

The first thermovision research, carried out using test stand for heat exchanges [15], revealed a number of mounting shortcomings in thermal insulation of the test stand. The thermal bridges were detected. It was also found that the foam insulation of the evaporator did not comply with the project requirements and resulted in high heat losses. The works were performed to eliminate the thermal bridges and extra thermal insulation was fitted to the evaporator. Subsequent research has shown that the heat losses lowered by nearly half in relation to previous thermographic diagnostic [15], i.e. around 13% (in other words, around 3900 W at total input power around 30000 W). It can be concluded that the heat loss results fall within the acceptable range (thus fulfilling design requirement) and hence there is no need for modification of thermal insulation on the heat exchangers test bench.

NOMENCLATURE

A	heat exchange surface area	[m^2]
h	specific enthalpy	[J/kg]
Q	thermal power	[W]
T	temperature	[K]
σ	Boltzmann constant	[W/m^2K^4]

Subscript

D	heat delivered to an evaporator
e	electrical
ORC	organic Rankine cycle
E	evaporator
R	regenerator
P	pipeline
C	condenser
L	losses
th	thermal
W	received heat from a condenser
HE	heat exchanger

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ACKNOWLEDGEMENT

The research work presented in this article was supported by the scientific project POIG.01.01.02-00-016/08 "Model agroenergy complexes as an example of distributed cogeneration based on local renewable energy sources".

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