11th International Conference "Environmental Engineering"
Vilnius Gediminas Technical University
Lithuania, 21–22 May 2020
Section: Energy for Buildings
http://enviro.vgtu.lt

eISSN 2029-7092 / eISBN 978-609-476-232-1

Article ID: enviro.2020.706
https://doi.org/10.3846/enviro.2020.706

Correct Selection of the ORC System Parameters for the Exhaust Gases Heat Source

Andrzej Grzebielec[1*], Artur Rusowicz[2], Tomasz Ziąbka[3]

[1, 2]Institute of Heat Engineering, Faculty of Power and Aeronautical Engineering,
Warsaw University of Technology, Warsaw, Poland
[3]ABZ Energia, Poland

Received 29 February 2020; accepted 24 march 2020

Abstract. Contrary to appearances, ORC (Organic Rankine Cycle) systems should not be selected for the highest available temperature of the upper heat source. This approach allows, of course, to achieve the highest energy efficiency, but this happens at the expense of the electrical power obtained. This solution would be good for an infinite heat source. In practice, there is always a finite heat source power. Therefore, the analysis should take into account other aspects than just maximum efficiency. The article presents a method of selecting ORC system parameters for a heat source in the form of waste gases, enabling the highest electrical power to be obtained. The analysis shows that even a significant reduction in the evaporation temperature of the working medium in the ORC system compared to the source temperature is beneficial for the profitability of investing in an ORC system. The analysis showed that for flue gases with temperatures of 300, 400, 500 and 600 °C, the best evaporating temperatures of the working medium in the ORC system are 145 °C, 185 °C, 214 °C and 250 °C, respectively. The highest level of generated electricity is obtained for these temperatures.

Keywords: ORC, energy efficiency, ORC working parameters, waste heat, exhaust gases, reduction of CO_2 emissions

Introduction

Due to human-induced climate change, technologies are sought that are able to reduce energy consumption. It turns out that the most sensible methods of reducing energy consumption are energy storage processes and the use of waste heat (Wardziak & Jaworski, 2017; Jaworski, 2019; Grzebielec et al., 2015; Owczarek & Baryłka, 2019; Cyklis & Janisz, 2015; Szelągowski & Trzcinkowski, 2019). One of the solutions enabling the use of waste heat are ORC systems.

In previous studies (Kajurek et al., 2017, 2019) it was determined which working fluid is best to be used in ORC systems. From the point of energy efficiency view, ammonia proved to be unrivaled, however, due to the fact that the temperature of the critical point for ammonia is 132.4 °C, it cannot be used in systems where a higher evaporator temperature in the ORC system is expected. Many popular fluids used in ORC devices have similar limitations, which is why in this analysis it was decided to remain at a higher level of generality and assuming top-down efficiency of heat exchangers and the efficiency of the ORC system in relation to the Carnot cycle.

The main purpose of the research is to determine what is the optimal evaporation temperature of the working medium in the ORC device for a heat source of known temperature, for the criterion of the maximum electric power generation.

1. Methodology

Organic Rankine Cycle (ORC) is an unconventional and very promising method of producing electricity that is becoming increasingly popular (Iglesias Garcia et al., 2018). The essence of installations based on ORC circuits boils down to the work of Steam Rankine Cycle (Laskowski et al., 2015) (Figure 1) with the difference that the working medium is not water, but organic or inorganic fluid characterized by low boiling point (Kajurek et al., 2017). Water, despite many advantages, which include: high heat of phase transformation, high specific heat in the liquid phase, chemical stability in a wide temperature range, low viscosity, non-toxicity, non-flammability or availability, it also has one special disadvantage - high normal boiling point of 100 °C, which eliminates its practical use in low-temperature

---

[*] Corresponding author. E-mail: *andrzej.grzebielec@itc.pw.edu.pl*

systems (Le et al., 2014). Organic fluids, in turn, are substances that have a low normal boiling point (refrigerants are most often used), often lower than 0 °C, so that ORC systems can operate at lower "drive temperatures" than systems with water (Lakew & Bolland, 2010; Averfalk et al., 2017).

The cycle shown in Figure 1 is implemented as follows. The waste heat is supplied to the ORC evaporator causing a change in the phase of the working medium from liquid to gas (lines 3-4-5). Then the working medium in gas phase goes to the turbine, driving an electric generator. Gas flowing through the turbine loses pressure (line 5-6). Next, the working gas flows into the regenerator exchanger, giving away heat – it cools down (line 6-7). Next, the working medium flows into the condenser (cooled by water or air), where it undergoes phase transformation and from the gas phase into the liquid phase (lines 7-8-1). The fluid in the liquid phase flows to the pump, where its pressure increases from point 1 to point 2. Then in the liquid phase it flows through the regenerator, in which it heats up from point 2 to point 3. Heated fluid goes to the evaporator (Macchi & Astolfi, 2016; Kajurek et al., 2017).

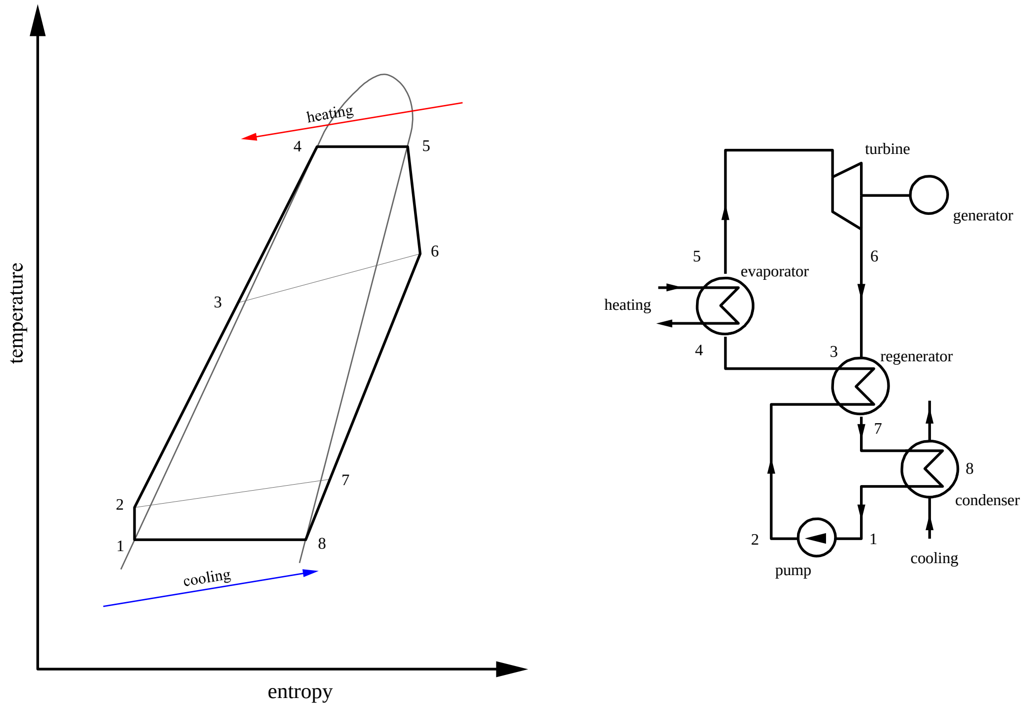

Figure. 1. General principle of Rankine Cycle

It is worth noting that an additional difference between typical cycle in power plants and ORC systems is also the fact that in power plants the system is designed to achieve the required electrical power by adapting the heat supply system to it. In the case of ORC, the driving source determines the structure of the rest of the system.

1.1. The ORC device efficiency

The efficiency of ORC systems η (Eq. (1)) is determined by the relationship describing the ratio of the electric power obtained in the generator P_{el} to "driving" power, i.e. the stream of heat supplied to the evaporator $\dot{Q}_{HS}$ (Desai & Bandyopadhyay, 2009; Kajurek et al., 2017).

$$\eta = \frac{P_{el}}{\dot{Q}_{HS}} . \tag{1}$$

Overall efficiency depends on the efficiency and effectiveness of individual system components (Kajurek et al., 2019):

- pump efficiency;
- isentropic turbine efficiency;
- mechanical turbine efficiency;
- generator efficiency;
- condenser thermal efficiency;
- evaporator thermal efficiency;
- regenerator thermal efficiency.

Efficiency also depends on the amount of additional energy needed to pump the cooling and heating medium through the exchangers (these are pumps or fans). The efficiency of ORC systems is primarily determined by the Carnot cycle η_c (Eq. (2)) (Colonna et al., 2015; Yu et al., 2013).

$$\eta_c = \frac{T_H - T_C}{T_H}, \tag{2}$$

where T_H is heat source temperature and the T_C is temperature of the cooling medium. According to Eq. (2), for a waste source with a temperature T_H = 90 °C (363 K), and cooling air temperature of T_C = 25 °C (298 K), the maximum efficiency that could be obtained from device is:

$$\eta_c = \frac{363-298}{363} = 0.179 = 17.9\%. \tag{3}$$

However, taking into account the previously mentioned real efficiency and effectiveness of individual elements of the system, the real efficiency is at the average level of 40% of Carnot's efficiency, so for the example it is 7.16%.

In summary, the higher the drive temperature (waste source temperature), and the lower cooling medium temperature, the higher efficiency of ORC system can be obtained.

2. Analyzed ORC system

In this research, the ORC system was analyzed, for which the upper source of heat is exhaust gases from various technological processes. They can be combustion, heating, quenching, etc. (Rusowicz et al., 2013). It was decided to check the optimal operating parameters for gas temperatures T_{H1} as 600 °C, 500 °C, 400 °C, 300 °C. Working fluid condensing temperature was established as T_C = 45 °C, what is typical seasonal temperature for air cooled heat exchangers in Poland. The volumetric flue gas stream was determined as 200 m^3/h. Gas is changing temperature from T_{H1} to T_{H2}, where T_{H2} depends on working fluid evaporate temperature T_E:

$$T_{H2} = T_E + 10K \tag{4}$$

to better illustrate the results, a variable ΔT was also introduced, which presents the temperature difference between the T_{H1} heat source and the evaporation temperature T_E of the working medium:

$$\Delta T = T_{H1} - T_E . \tag{5}$$

This variable is very useful for ORC installation designers.

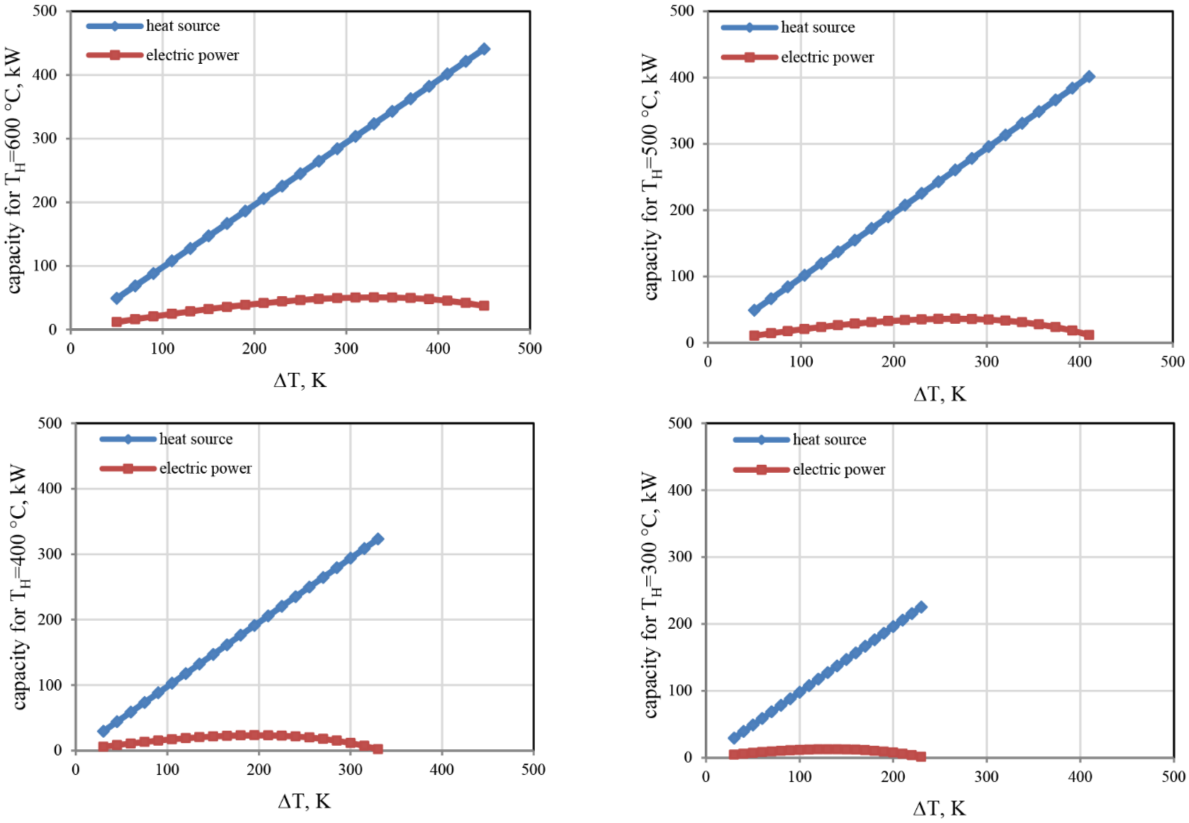

Figure 2. Electric power and driving heat capacity for 600, 500, 400, 300 °C driving temperature as a function of ΔT

3. Results

Figure 2 presents the results of the ORC device capacity analysis for four different T_H drive temperatures.

In all cases presented in Figure 2, it turned out that there is an optimal evaporation temperature, for which the device reaches the maximum electric power and what is the most important, this is not a value at the level of the maximum possible temperature in the evaporator. Figure 3 shows the aggregated results of the electrical power capacity obtained for four different driving temperatures as a function of ΔT.

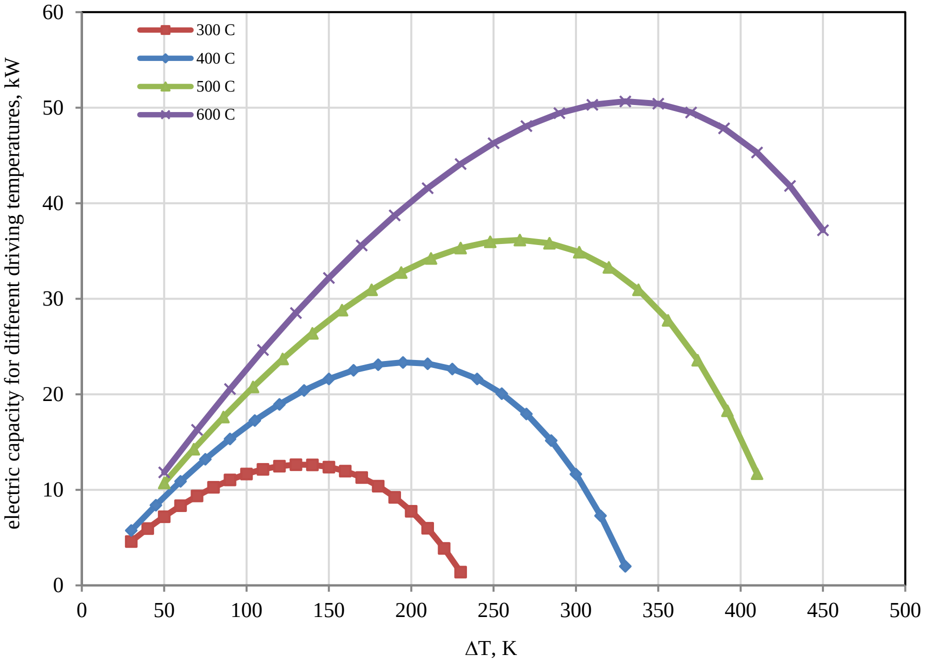

Figure 3. Electric capacity of ORC device as a function of ΔT for 300, 400, 500, 600 driving temperature

Figure 4 presents the same results, but as a function of evaporation temperature of the working medium T_E. In both figures, the maximum values are *145 °C* for $T_H = 300$ °C, *185 °C* fot $T_H = 400$ °C, *214 °C* for $T_H = 500$ °C, and *250 °C* for $T_H = 600$ °C.

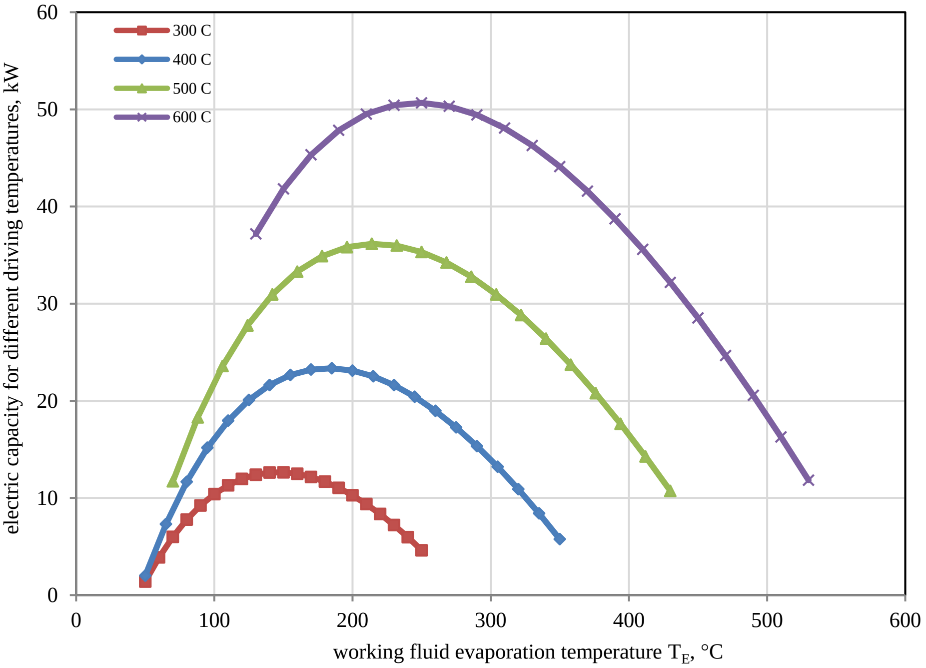

Figure 4. Electric capacity as a function of working fluid evaporation temperature

Figures 5 and 6 show how the efficiency of the ORC device as a function of ΔT (Figure 5) and as a function of evaporation temperature T_E of the working fluid (Figure 6). In both cases there is no maximum value because according to theory (Eq. (2)) the greater the temperature difference between the lower and upper heat sources, the higher the efficiency.

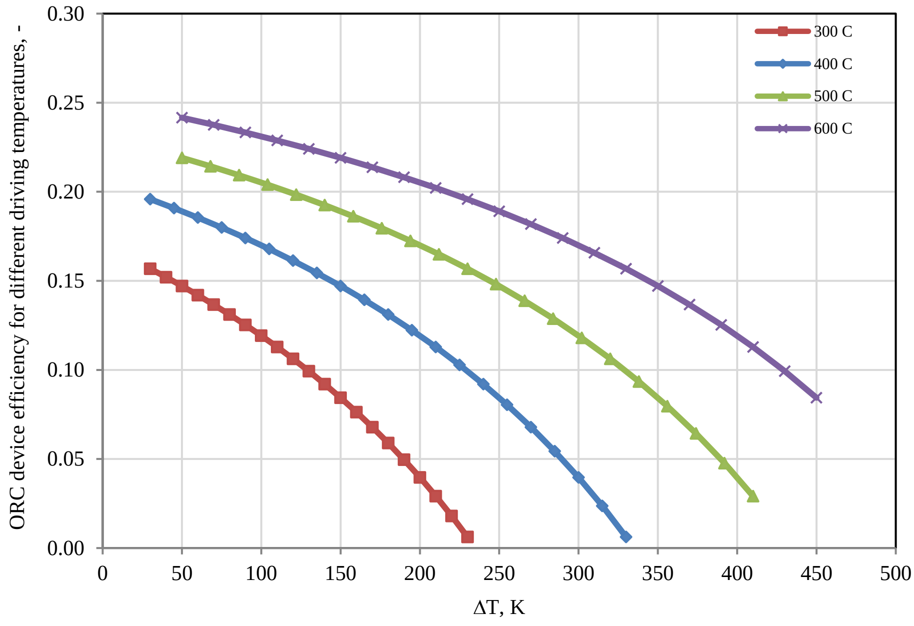

Figure 5. ORC device efficiency as a function of ΔT

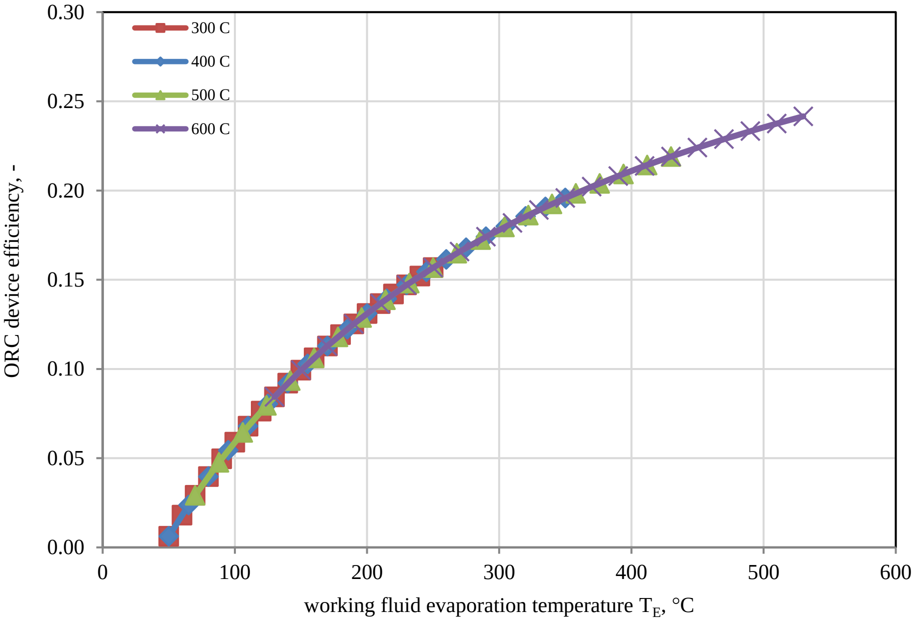

Figure 6. ORC device efficiency as a function of working fluid evaporation temperature T_E

Conclusions

The obtained modeling results show that it is not the best solution to achieve the highest energy efficiency ratio of the ORC system. For a finite heat source with high temperature it is possible to determine the optimum temperature of the working medium should be heated in the ORC evaporator (evaporation temperature). The optimal evaporation temperatures for the energy source as 200 m^3/h exhaust gases at four different driving temperatures: 300 °C, 400 °C, 500 °C and 600 °C were determined in the analysis. The analysis showed that the optimal evaporation temperatures were: 145 °C, 185 °C, 214 °C, 250 °C respectively. The best thermal efficiency according to theory is the highest at the highest source temperatures. On the other hand, the effectiveness for optimal temperatures are: 9.5, 12.2, 13.9, 15.7% respectively. The research results presented in this article can be a great help when designing ORC devices for waste heat in the form of exhaust gases.

Acknowledgements

The article was written as part of the project entitled: “ISEE-P – Inteligentne sterowanie efektywnością energetyczną dla przemysłu” (ISEE-P – intelligent energy efficiency control for industry). This is a project under Działania 1.2: “Sektorowe programy B+R” Programu Operacyjnego Inteligentny Rozwój 2014–2020, co-financed from the European Regional Development Fund.

Fundusze Europejskie
Inteligentny Rozwój

Rzeczpospolita Polska

Unia Europejska
Europejski Fundusz Rozwoju Regionalnego

References

Averfalk, H., Ingvarsson, P., Persson, U., Gong, M., & Werner, S. (2017). Large heat pumps in swedish district heating systems. *Renewable and Sustainable Energy Reviews*, *79*, 1275–1284. https://doi.org/10.1016/j.rser.2017.05.135

Colonna, P., Casati, E., Trapp, C., Mathijssen, T., Larjola, J., Turunen-Saaresti, T., & Uusitalo, A. (2015). Organic rankine cycle power systems: From the concept to current technology, applications, and an outlook to the future. *Journal of Engineering for Gas Turbines and Power*, *137*(10), 100801. https://doi.org/10.1115/1.4029884

Cyklis, P., & Janisz, K. (2015). An innovative ecological hybrid refrigeration cycle for high power refrigeration facility. *Chemical and Process Engineering – Inzynieria Chemiczna i Procesowa*, *36*(3), 321–30. https://doi.org/10.1515/cpe-2015-0022

Desai, N. B., & Bandyopadhyay, S. (2009). Process integration of organic rankine cycle. *Energy*, *34*(10), 1674–1686. https://doi.org/10.1016/j.energy.2009.04.037

Grzebielec, A., Rusowicz, A, Jaworski, M., & Laskowski, R. (2015). Possibility of using adsorption refrigeration unit in district heating network. *Archives of Thermodynamics*, *36*(3), 15–24. https://doi.org/10.1515/aoter-2015-0019

Iglesias Garcia, S., Ferreiro Garcia, R., Carbia Carril, J., & Iglesias Garcia, D. (2018). A review of thermodynamic cycles used in low temperature recovery systems over the last two years. *Renewable and Sustainable Energy Reviews*, *81*(Part 1), 760–767. https://doi.org/10.1016/j.rser.2017.08.049

Jaworski, M. (2019). Mathematical model of heat transfer in PCM Incorporated fabrics subjected to different thermal loads. *Applied Thermal Engineering*, *150*, 506–511. https://doi.org/10.1016/j.applthermaleng.2019.01.019

Kajurek, J., Rusowicz, A., Grzebielec, A., Bujalski, W., Futyma, K., & Rudowicz, Z. (2019). Selection of refrigerants for a modified organic rankine cycle. *Energy*, *168*, 1–8 https://doi.org/10.1016/j.energy.2018.11.024

Kajurek, J., Rusowicz, A., Grzebielec, A., Bujalski, W., Futyma, K., Szczęśniak, A., & Rudowicz, Z. (2017). Influence of working fluid properties on performance of organic rankine cycle. *Rynek Energii*, 2, 68–79.

Lakew, A. A., & Bolland, O. (2010). Working fluids for low-temperature heat source. *Applied Thermal Engineering*, *30*(10), 1262–68. https://doi.org/10.1016/j.applthermaleng.2010.02.009

Laskowski, R., Rusowicz, A., & Grzebielec, A. (2015). Estimation of a tube diameter in a "church Window" condenser based on entropy generation minimization. *Archives of Thermodynamics*, *36*(3), 49–59. https://doi.org/10.1515/aoter-2015-0021

Le, Van L., Kheiri, A., Feidt, M., & Pelloux-Prayer, S. (2014). Thermodynamic and economic optimizations of a waste heat to power plant driven by a subcritical ORC (Organic Rankine Cycle) using pure or zeotropic working fluid. *Energy*, *78*, 622–638. https://doi.org/10.1016/j.energy.2014.10.051

Macchi, E., & Astolfi, M. (2016). *Organic Rankine Cycle (ORC) power systems: Technologies and applications*.

Owczarek, M., & Baryłka, A. (2019). Determining the thermal diffusivity of the material based on the measurement of the temperature profile in the wall. *Rynek Energii*, 4(*143*), 63–69.

Rusowicz, A., Grzebielec, A., & Ruciński, A. (2013). Analysis of the gas turbine selection by the pinch point technology method. *Przemysl Chemiczny*, *92*(8).

Szelągowski, A., & Trzcinkowski, P. (2019). Experimental study on the adsorption refrigeration device built on a water-silica gel working pair. *Modern Engineering*, 1, 42–54.

Wardziak, Ł., & Jaworski, M. (2017). Computer simulations of heat transfer in a building integrated heat storage unit made of PCM composite. *Thermal Science and Engineering Progress*, *2*, 109–118. https://doi.org/10.1016/j.tsep.2017.05.006

Yu, G., Shu, G., Tian, H., Wei, H., & Liu, L. (2013). Simulation and Thermodynamic analysis of a bottoming Organic Rankine Cycle (ORC) of Diesel Engine (DE). *Energy*, *51*, 281–290. https://doi.org/10.1016/j.energy.2012.10.054