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Utilisation of bleed steam from power plant to increase saturation temperature in organic Rankine cycle

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Abstract

In the paper presented is a novel concept to utilize the heat from the turbine bleed to improve the quality of working fluid vapour in the organic Rankine cycle (ORC), which contributes to the increase of ORC efficiency and the overall efficiency of the combined system of the power plant and ORC plant. Calculations have been accomplished for the case when available is waste heat as a flow rate of hot water at a temperature of 90 °C, which is used for preliminary heating of working fluid in ORC cycle. That hot water is obtained as a result of conversion of exhaust gases from power plant to the energy of hot water. Then the working fluid in ORC is further heated by the bleed steam to reach 120 °C. Such vapour is subsequently directed to the turbine. Possible working fluids were examined, namely R134a, silicone oils MM and MDM, toluene, and ethanol. Only under conditions of 120 °C/40 °C the silicone oil MM showed the best performance, in all other cases the ethanol proved to be best performing fluid of all. Results are compared with the 'stand alone' ORC module showing its superiority.

Keywords: ORC; Increase of upper source temperature; Bleed steam utilisation

1 Introduction

In the paper presented is a novel way to the utilization of waste heat available from the power plant to produce electricity in the organic Rankine cycle (ORC) system. The waste heat is assumed to be in the form of a stream of hot water having a temperature of 90 °C. This water is obtained as a result of heat recovery from exhaust gases from the power plant. Waste heat as a stream of hot water can then be used in a heat exchanger (steam generator) to change the state of the

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working fluid in the ORC installation. Due to the relatively low temperature of the stream of hot water the performance parameters established in this way, i.e., the saturated vapor of the organic fluid working in the ORC system is insufficient to obtain a high conversion rate to electricity in the ORC cycle. Considered by the author were different ways to raise the temperature of the upper heat sources to increase the ORC efficiency. Considered were solar panels [1] and heat pumps [2], as well as a reduction in condensing temperature through the heat dump to the ground [3]. Application of the above treatments is aiding to achieve better performance the ORC system (higher efficiency), but unfortunately for example solar panels, cannot operate all day in Polish conditions, so cannot be therefore considered as the basis for the professional ORC installation. Another negative outcome is the huge investment costs involved in these cases. Conclusion from the studies [1–3] was that further opportunities to raise the temperature of the upper or lower heat reservoir must be sought. Such possibilities are, however, limited.

This paper proposes an original approach to increase temperature of the vapour of working fluid at the inlet to the turbine through the use of heat from the bleed steam from the low-pressure (LP) part of the turbine. It is a concept which the author have not met previously in the literature. Another advantage here is the fact that the low-temperature cycles better fill the area of wet vapour region in the lower temperature range and bring in such way these cycles closer to the ideal thermodynamical cycles. Secondly, the efficiency of the LP turbine part is much lower with steam as working fluid than the low-boiling point fluid in ORC turbine. It is usually assumed that the efficiency of the last stage of the steam turbine is about 60% while the organic fluid turbine efficiency can be assumed at the level of 85%. It is the another gain from the implementation of such a concept of so called 'bottoming of the power cycle'.

There are in the literature solutions regarding the sole use of heat of the bleed steam to drive the operation of the ORC installation. One of the examples is based on the use of the total heat contained in the steam bleed treated as a heat source to the ORC [4]. The concept show the superiority of such solution over the installation, which does not have integration with the ORC installation. Proposed concept is improved, because it consists in the fact that apart from the waste heat, here in the form of the stream of hot water, additional heat from the bleed is used to enhance parameters of steam in the ORC installation. Presented in this paper calculations are only preliminary, as the author wanted to present the idea of utilisation of the steam bleed to raise temperature of working fluid in ORC installation. Full calculations will require optimization of the cooperation of the upper source (heat from the bleed) and the ORC cycle, so that the exergy losses in the whole system are as small as possible.

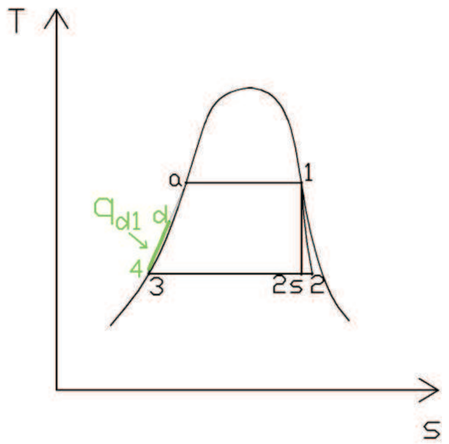
2 A concept of reheating the ORC system

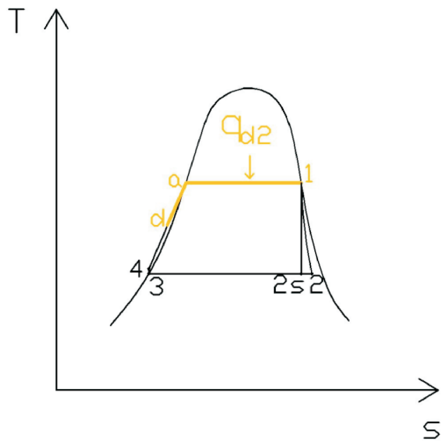
The concept of using heat from the steam extraction is assumed to heat-up the working fluid in the ORC plant in two stages. The precondition of the study was to use the waste heat in the form of a stream of hot water at 90 °C, recovered from the exhaust gases. Such low enthalpy heat source is rather insufficient to produce a good quality vapour to feed the turbine. That was incentive to search for the ways of increasing the temperature of the vapour at ORC turbine inlet. In author opinion the steam from extraction point fits very well that idea. Therefore, in this paper presented will be calculations with the rate of supplied waste heat in the amount of 5 MW to the ORC in the form of stream of hot water at 90 °C, although it is potentially possible to use even 100 MW of waste heat. Subsequently the steam from the extraction will be used in the specified fraction to raise further temperature of working fluid.

Delivery of waste heat, see Fig. 1a, starts at the point 4, if the cycle is without internal heat recovery to the point of vapour saturation, marked on the diagram as the point d. The second stage of heating provides the heat supply, using for this purpose one of the streams of bleed steam from the steam turbine, originally used to preheat the boiler feedwater, Fig. 1b. Part of the stream of steam is routed to the ORC cycle to superheat the vapour from point d to point 1. In the present study it was assumed that temperature of working fluid vapour before the ORC turbine will be 120 °C, however that temperature will be further corrected from the point of view of optimum utilisation of heat from the extraction. Remaining part of the steam from extraction point is used for preheating of the boiler feedwater, Fig. 2. It must be remembered that the heat directed to the feed-water heater will be smaller than that without the ORC. In Fig. 2 this is indicated by the node no. 6. Steam parameters in the node 6, together with the parameters of nodes at entry and exit from the regenerative heat exchanger, are presented in Tab. 1.

Table 1. The values of parameters before and after the heat exchanger used for superheating

Reference power plant	Unit	Value
Temperature of the extraction point	°C	228.8
Pressure at the extraction point	MPa	0.2519
Liquid saturation temperature at extraction pressure	°C	127.66
Mass flow rate at extraction point	kg/s	23.03
Enthalpy at extraction point	kJ/kg	2926.7
Liquid enthalpy at extraction point pressure	kJ/kg	536.41
Available rate of heat	MW	55.048





a) b)

Figure 1. a) Heating of working fluid realised by the flow rate of waste heat. b) Superheating of the working fluid using the steam from extraction.

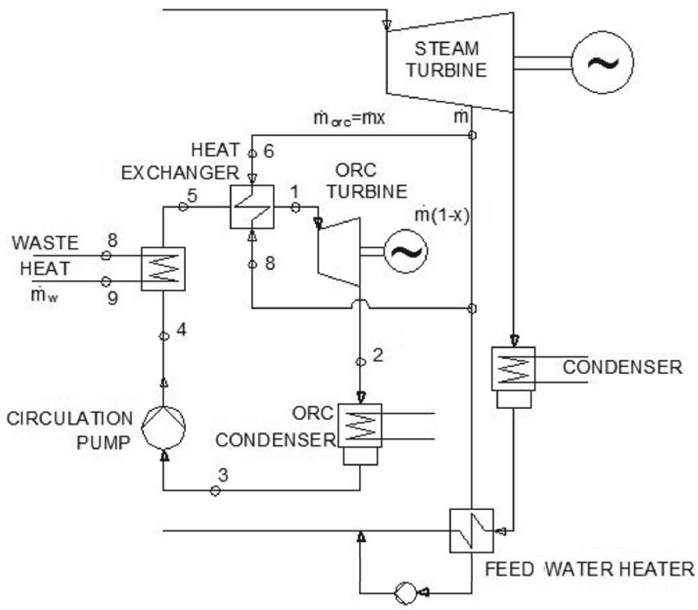


Figure 2. A general concept of heat supply to ORC installation with internal heat regeneration.

Diagram of ORC installation with connections to steam bleeds is shown in Fig. 2. Only a portion of the steam stream is directed to the working fluid vapour superheater (heat exchanger – HE) in the low-temperature ORC installation. The

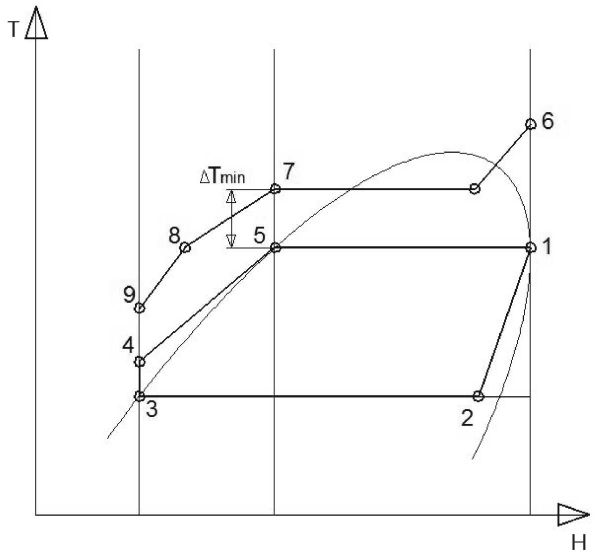


Figure 3. Cooperation of available heat sources with the ORC cycle.

exact amount of steam to be used for that purpose depends on the type of the working fluid in ORC installation. There must be obeyed the condition that the working fluid in ORC installation can be heated by the source, which at all conditions exceeds the minimum temperature difference, ΔT_{min}, so called 'pinch point' between the hot fluid and working fluid, as shown in Fig. 3. It is our intention, that the waste heat is heating the working fluid between the states 8 and 9. The remaining heat comes from the steam, which is first desuperheated, then condensed and subsequently subcooled. Such arrangement assures a correct cooperation of the heat sources with the ORC installation.

According to that the relation between the amount of steam from the extraction to the ORC working fluid determines the final temperature of steam after the heat exchanger. In the study it was assumed a value $T_8 = 90\,^{\circ}C$. Following condensation and subcooling the liquefied steam is discharged to the feed water heat exchanger warming the boiler feed water. The remaining part of steam, which did not take part in supplying the ORC installation in the amount of (1-x) heats the boiler feed water in the regenerative heat exchanger as originally envisaged.

An important step in case of using some of the bleed steam for heating of working fluid in ORC system is to balance the profit performance of the electricity produced in the ORC system with respect to the heat lost in the feed water heating, which, on the other hand, contributes to reduction of the overall power plant efficiency and reduces the power produced by the steam turbine of the power plant. Therefore in the analysis presented below the quantities taken into account in this situation are: the difference of electricity produced in the power plant cooperating with the ORC installation and the energy produced by the power plant itself and ORC installation alone, without extra reheating. In case of the ORC installation with heating using the bleed steam the upper heat source temperature is assumed as 120 °C whereas in case when ORC system has no extra input of heat then the upper heat source is at 80 °C. The condensation temperature has been assumed at two levels, i.e., 40 °C and 10 °C, corresponding to summer and winter conditions.

Thermal power available from the extraction point is 55.113 MW. The efficiency of the reference electricity generation plant if no steam is taken for supplying the ORC installation is $\eta_b = 49.1\%$. If some steam from the bleed is taken to aid the ORC installation that overall efficiency is to decrease. The benefits of the presented in the paper approach stem from the fact that a certain amount of additional heat is brought into circulation from a source of cheap, waste heat and in that way improving performance of the ORC cycle which additionally is fed through the steam bleed. In effect the installation as a whole should produce more electricity than otherwise.

3 Calculation results

The ORC installation performance depends strongly on the used working fluid. In the present paper five working fluids were considered namely R134a, ethanol, two silicone oils MM, MDM, and toluene. Their main characteristics is presented in Tab. 2 The appropriate commercial software was used for the calculations of thermal properties.

Presented below is the calculation procedure for calculation of ORC cycle efficiency:

1. turbine power – $P = \dot{m}_{ORC}(h_1 - h_2)$,
2. generator power – $P = P_T \eta_G$,
3. rate of heat of evaporator - $\dot{Q} = \dot{m}_{ORC}(h_1 - h_4)$,
4. rate of heat in regenerator – $\dot{Q}_{RWC} = \dot{m}_{ORC}(h_2 - h_1) = \dot{m}_{ORC}(h_n - h_4)$,
5. pump power – $P_p = \frac{\dot{m}_{ORC}(h_4 - h_3)}{\eta_p}$,
6. total efficiency without regenerator - $\eta_{ORC} = \frac{P_T - P_P}{\dot{Q}}$.

Below are presented in tables, the values of key parameters in the characteristic points of the organic Rankine cycle for different working fluids. The calculations have been accomplished for the following fluids: ethanol, R134a, toluene, MM and MDM.

Table 2 summarizes the overall efficiency of the ORC, depending on the type of working fluid and the temperature difference between upper and lower sources. For a better comparison of results obtained in the attached table, the theoretical maximum Carnot efficiency for a given temperature range has also been calculated.

Table 2. ORC cycle efficiency for each fluid and the flow temperature (upper source) and condensation (cold side) * – efficiency of the regeneration cycle.

Fluid	Temperature of upper/lower heat source [°C]			
	80/40	80/10	120/40	120/10
Carnot efficiency	0.113	0.198	0.204	0.280
R134a	0.077	0.129	0.082 0.099*	0.137 0.159*
Ethanol	0.090	0.153	0.093 0.096*	0.156
MM	0.079 0.089*	0.129 0.152*	0.072 0.092*	0.121 0.168*
MDM	0.078 0.089*	0.126 0.152*	0.007 0.092*	0.117 0.168*
Toluene	0.088	0.148	0.088 0.099*	0.151 0.165*

The highest theoretical efficiency is obtained in case of the silicone oil MM. This is for the case of sources with temperatures 120/10 °C. Noteworthy is a high efficiency of ethanol in all examined temperature ranges. It should be noted that in this case there is no need for expensive regenerative heat exchanger. This working fluid is also the cheapest and most environmentally friendly.

The presented results of calculations show that a more profitable trend for increasing of the Rankine cycle efficiency is to lower the temperature of the lower heat source. Increase of efficiency is almost twice bigger as compared to the treatment in which temperature of the higher heat source is increased. Analysis of the physical properties, calculation results and economic aspects indicates however that it is the ethanol which is the most attractive working fluid for application in the considered low-temperature ORC system. The remainder of this work concerns calculations using ethanol as the working fluid.

In order to determine the mass flow rate of working fluid in the ORC system we are using the energy balance of the supplied waste heat which is the product of mass flow rate and enthalpy difference between point d and 4:

$$\dot{Q}_d = \dot{m}_{ORC}(h_d - h_4) \; . \tag{1}$$

If we assume 5 MW of heat supplied in such way than we can determine the flow rate of working fluid in the ORC installation from Eq. (1). Two cases are considered. In the first case the mass flow rate is calculated for a condenser temperature of 40 °C – summer, whereas in the second one the mass flow rate is calculated for a temperature of 10 °C, corresponding to winter conditions. The calculated values are 5.35 kg/s for the conditions of 120/40 °C and 4.79 for 120/10 °C, respectively.

Of course in the winter in ORC installation there will circulate the same amount of working fluid as in summer. In such case however we will have a noticeable advantage in the production of electricity in favour of winter conditions. Calculations of the mass flow rate of bleed steam, which is needed to ensure the working fluid superheat to be raised to 120 °C, are conducted on the basis of the balance of thermal power in the heat exchanger HE1, as shown in Fig. 1b. Mass flow rate of organic fluid increases its enthalpy from point d to point 1. In the second leg of the HE1 the bleed steam changes its enthalpy from the point 6 to 8. We assume that the steam will be desuperheated, condensed and subsequently subcooled, as shown in Fig. 3. At the point 8 we will have a liquid state at a pressure the same as in point 6 but at temperature of 110 °C. Obtained results are presented in Tab. 3.

Table 3. Values of parameters in the characteristic points of the vapour superheater.

Node no.	Temperature [°C]	Pressure [bar]	Enthalpy [kJ/kg]	Mass flow rate [kg/s]
6	228.8	2.519	2926.7	23.03
8	90.0	2.519	377.18	23.03
d	80.0	1.0857	1267.0	5.34/4.79
1	120.0	1.0857	1342.3	5.34/4.79

Temperature of point 8 was set at 90 °C, which means that at that pressure the vapour was first desuperheated, then condensed at saturation temperature of 127 °C and subcooled to 90 °C. Enthalpy point of 8 was calculated on the basis of a given pressure and temperature. Knowing the value of the remaining components of the equation, it is possible to calculate the mass flow rate of bleed steam, $\dot{m}_u$, directed from a bleed steam to organic fluid to obtain its desired temperature equal to 120 °C:

$$\dot{m}_{ORC}(h_1 - h_d) = \dot{m}_u(h_6 - h_8) . \tag{2}$$

Equation (2) enables determination of the flow rate of bleed steam in aiding the ORC system. In effect for the conditions of 120/40 °C the flow rate of steam used in the ORC is 0.16 kg/s, whereas for 120/10 °C it is 0.14 kg/s, respectively. Due to supply of heat from the bleed the ORC system gets additional thermal power, calculated as

$$\dot{Q}_u = \dot{m}_u(h_6 - h_8) \ . \tag{3}$$

The heat input to HE1 at different working conditions of 120/40 °C (summer) and 120/10 °C (winter) is equal to 401.84 kW and 359.93 kW, respectively. The total thermal power $\dot{Q}_{ORC}$, is the sum of the thermal power supplied from waste heat and heat input $\dot{Q}_d$ from the bleed steam $\dot{Q}_u$

$$\dot{Q}_{ORC} = \dot{Q}_d + \dot{Q}_u \ . \tag{4}$$

The total thermal power supplied to ORC cycle is 5401.84 kW for the temperature conditions 120/40 °C and 5359.93 kW for 120/10 °C, respectively. On that basis the power generated in the ORC cycle can be calculated from the formula

$$N_e = \eta_{ORC}\dot{Q}_{ORC} = \eta_{ORC}(\dot{Q}_d + \dot{Q}_u) \ . \tag{5}$$

The net amount of generated power is 500.21 kWe under conditions of 120/40 °C and 837.76 kWe under conditions 120/10 °C, respectively. Thermal power removed from the reference power plant for aiding the ORC cycle is 401.84 kW for 120/40 °C and 359.93 kW for 120/10 °C, respectively. The thermal power at the efficiency of electricity generation of $\eta_b = 0.491$ and the gross electric output of $N_T = 900$ MWe is $Q = N_T/\eta_b = 1833.0$ MW.

The amount of electrical power generation in the reference power plant varies with the removal of heat from the primary power plant to the ORC installation in the following way:

$$N_T = \eta_b(\dot{Q} - \dot{Q}_W) \ . \tag{6}$$

Decrease of electrical power production in the primary electric power plant is hence calculated by the formula $\Delta N_T = N_T - N_T'$, and the results are presented in Tab. 4. That amount of energy could be produced if the heat from the bleed did not aid the low-temperature ORC installation.

Table 4. Reduction in electric power generation in the primary plant.

Case	Power [kWe]
ΔN_{T1}(120/40 °C)	197.3
ΔN_{T1}(120/10 °C)	176.6

Presented there are also results of calculations for the case where ORC is regarded as a stand alone unit and not utilising the heat from the extraction point. In this case situation is a little bit complex as we are dealing with a single phase waste heat medium. In order to supply 5 MW of heat into the ORC working fluid we must ensure that there is preserved a minimum 5 K pinch temperature between the heating fluid and working fluid. That means that either the flow rate of hot water will be large and temperature drop of hot water small or vice versa. In order to perform required calculations we perform the estimate of the ratio of mass flow rate of waste hot water, ($\dot{m}_W$) to the flow rate of working fluid in ORC installation. In such case we have the balance of exchanged heat required to evaporate the ORC working fluid:

$$\dot{m}_W C_P (T_6 - T_{pinch}) = \dot{m}_{ORC} h_{lv}(T_1) \; . \tag{7}$$

Expression (7) enables calculation of the function of $\dot{m}_W/\dot{m}_{ORC}$ in function of evaporation temperature of working fluid in ORC installation and minimum pinch temperature from the expression:

$$\Delta T_{min} = T_{pinch} - T_1 = (T_6 - T_1) - \frac{h_{lv}(T_1)}{\frac{\dot{m}_W}{\dot{m}_{ORC}} C_P} \; . \tag{8}$$

In calculations it was assumed that the pinch temperature is ΔT_{min}=5 K, and temperature of evaporation in ORC installation varied from 90 °C to 50 °C. The results with a corresponding values of thermal efficiency are presented in Tab. 5. The results of all accomplished calculations are presented in Tab. 6.

Table 5. Comparison of the results of calculations for the stand alone ORC system.

	Unit	Waste water inlet temperature/boiling temperature			
		90/80	90/70	90/60	90/50
Efficiency of ORC system	–	0.107	0.084	0.058	0.014
Mass flow rate in waste heat water	kg/s	216.29	73.50	44.87	32.55
Electrical power of ORC	kW	552.66	425.9	292.11	66.87
Waste water outlet temperature T_7	°C	84.50	73.76	63.40	53.34

The results indicate that the use of energy from the steam turbine extraction may be an attractive option to increase the temperature of the upper source temperature in the ORC system. The stand alone installation generates power dependent upon the ratio of waste water mass flow ratio to the mass flow ratio in ORC installation. Another parameter there is the evaporation temperature, which influences the performance of the system. Theoretically in case of evaporation temperatures of 80 °C the production of electricity in the stand alone ORC system is better than in case with utilization of extraction steam. In such case there will

Table 6. Comparison of the results of calculations.

	Unit	ORC with steam from extraction	
		120/40	120/10
Efficiency	–	0.093	0.156
Mass flow rate in ORC	kg/s	5,35	4.79
Mass flow rate from bleed	kg/s	0.16	0.14
Electrical power of ORC	kW	500.21	837.76
Power lost in reference plant	kW	197.3	176.6

be however excessive power involved in circulation power required to drive the pump as such case requires a large mass flow rate of hot water to be circulated. In all other cases we can observe the superiority of the case with extraction steam. In such case the exergy losses are smaller than in the stand alone case due to better adjusted temperature differences between the source of heat and the working fluid. In must be remembered that all calculations presented in Tabs. 5 and 6 are for the case of internal efficiency in turbines equal unity. Incorporation of the internal efficiencies will contribute to even more pronounced differences in favour of extraction steam case.

4 Conclusions

In the paper presented is a novel concept to utilize the heat from the turbine bleed to improve the quality of working fluid vapour in the low-temperature ORC cycle. That is a completely novel solution in the literature which also shows its superiority over the system which would not be reheated by the bleed steam from extraction. Utilisation of additional heat leads to more efficient and more readily available turbines due to a greater mass flow rate of working fluid. It must be remembered that the waste water at outlet from the evaporator could further be used for other purposes for example for preliminary drying of the coal, introducing in such way a cogenerative process and improving further the efficiency of the cycle.

Calculations have been accomplished for the case when available is a flow rate of hot water at a temperature of 80 °C, which is used for preliminary heating of working fluid. That hot water is obtained as a result of conversion of exhaust gases to the energy of hot water. Then the working fluid is further heated by the bleed steam to reach 120 °C. Such vapour is directed to the turbine. In the paper [5] possible working fluids were examined, namely R134a, MM, MDM, toluene and ethanol. Only under conditions of 120/40 °C the silicone oil MM showed the best performance, in all other cases the ethanol proved to be best.

The obtained effect in comparison to the stand alone system, i.e., the installation which uses only waste heat, shows its superiority in all cases of evaporation temperature. The use of waste heat at a temperature of 90 °C in the ORC cycle with ethanol as working fluid seems to have great potential. In case of the upper medium temperature of 80 °C, the theoretical efficiency is of the order of 9.3% (summer) and 15.6% (winter) compared with Carnot efficiency of 11.33% and 19.82%) in case of utilization of the extraction steam.

The proposed approach can also be used in other situations, where a low-temperature heat source is used for driving ORC installation, such as geothermal heat or other process heat.

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References

[1] Mikielewicz D., Wajs J., Gliński M., Mikielewicz J.: *Analysis of possibilities of utilisation of heat pumps for increasing working fluid parameters in ORC power plant.* Rep. IFFM PAS 79/2011 (in Polish).

[2] Mikielewicz D., Wajs J., Gliński M., Mikielewicz J.: *Analysis of possibilities of utilisation of solar collectors for increasing working fluid parameters in ORC power plant.* Rep. IFFM PAS 395/2011 (in Polish).

[3] Mikielewicz D., Wajman M.: *Investigations into possibility of condenser cooling in ORC power plant using the ground as the low-temperature heat reservoir.* Rep. IFFM PAS 368/2011 (in Polish).

[4] Angelino G., Invernizzi C., Molteni G.: *The potential role of organic bottoming Rankine cycles in steam power stations.* Proc. IMechE, Part A, **213**(1999), 75–81.

[5] Mikielewicz D., Mikielewicz J.: *Utilisation of bleed steam heat to increase the upper heat source temperature in low-temperature ORC.* Arch. Thermodyn. **32**(2011), 3, 57–70, DOI: 10.2478/v10173-011-0013-5.