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MANAGEMENT OF LOW GRADE WASTE HEAT FROM THE SUPERCRITICAL POWER PLANT USING THE ORC INSTALLATION AIDED BY BLEED STEAM

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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 bottoming ORC installation. That is a completely novel solution in the literature, 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 a flow rate of low enthalpy hot water at a temperature of 90°C, which is used for preliminary heating of the working fluid. That hot water is obtained as a result of conversion of exhaust gases in the power plant to the energy of hot water. Then the working fluid is further heated by the bleed steam to reach 120°C. Such vapour is subsequently directed to the turbine. In the paper 5 possible working fluids were examined, namely R134a, MM, MDM, toluene and ethanol. In all cases the ethanol proved to be best performing fluid of all. Results are compared with the “stand alone” ORC module showing its superiority.

INTRODUCTION

In the paper presented is a novel way to the utilization of low enthalpy heat available for example from the heat recovery from exhaust gases from the power plant to produce electricity in the Organic Rankine Cycle (ORC) system. The low enthalpy waste heat is assumed to be in the form of a stream of hot water having temperature of 90^{o}C. Waste heat as a stream of hot water can then be used in a heat exchanger (vapour generator) to change the state of the working fluid in the ORC installation from liquid to vapour state (dry saturated vapour). Due to the relatively low temperature of the stream of hot water the performance parameters established in this way, i.e. the saturated vapour of the organic fluid working in the ORC system is insufficient to obtain a high conversion rate to electricity in the ORC system. Considered by the authors 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 of the ORC system (higher efficiency), but unfortunately such technologies cannot be considered as the basis for the professional ORC installation. Another negative outcome of use of solar collectors or heat pumps is the huge investment costs involved. Therefore other ways 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 ORC working fluid at the inlet to the turbine through the use of heat from the bleed steam from the low-pressure part of the steam turbine of the reference power plant. It is a concept which the authors 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 the so called “bottoming 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 authors of that concept show the superiority of such solution over the installation, which does not have integration with the ORC installation. Proposed by the authors 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 is used from the bleed to enhance parameters of steam in the ORC installation. Use of steam from the extraction point has an advantage that it can be condensed in the process of heating of ORC working fluid and in such way is better from the exergy destruction point of view. Using the waste heat only to heat liquid phase of working fluid contributes to better utilisation of waste heat. Presented in this paper calculations are preliminary, as the authors wanted to present the idea of utilisation of the steam bleed to raise temperature of working fluid in ORC.

CASES OF HEAT SUPPLY

Generally there can be distinguished two cases of interaction of the heat source with ORC, namely the heat can be supplied to the evaporator by the single-phase fluid or a phase changing fluid. In the paper the simple Rankine Cycle is considered, consisting namely of the evaporator, turbine, condenser and circulation pump. In case of dry fluid the internal regeneration is considered. The working fluid is in the state of saturated liquid at the exit of the condenser; it is then pumped to the evaporator where it gains heat from the heat source. The working fluid at the exit of the evaporator is saturated vapor. Hot pressurized working fluid expands in the turbine thereby performing useful work.

Heat supply by the single phase fluid

The most common way of providing heat to the ORC installation is by means of the single-phase fluid. Such situation is schematically shown in Figure 1. In the considered case it is required that throughout the entire heating period there is sustained a minimum pinch point temperature difference ΔT_{min} equal to at least 5K. There is however a possibility of the pinch point occurring not at the node 5 but 1 or 4, but such cases will not be considered in the present study. The study of cooperation of the ORC system with the heat source exhibiting temperature variation was presented by the authors in [5].

The heat balance of the evaporator yields:

$$\dot{m}_{ORC}\left(h_1 - h_4\right) = \dot{m}_w\left(h_6 - h_{10}\right) \qquad (1)$$

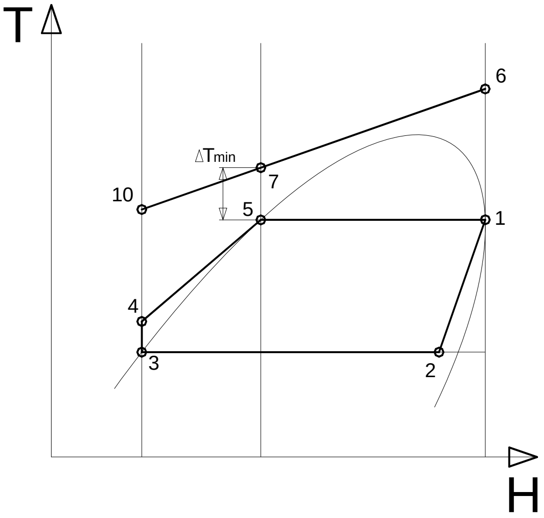

Figure 1 Schematic of heat supply to the ORC installation by means of the single phase fluid

It ought to be remembered that transition from enthalpy h_4 to enthalpy h_1 of working fluid in ORC installation consists first of heating of the fluid to evaporation temperature T_1 and its subsequent evaporation, hence enthalpy h_1 and, similarly, enthalpy h_{10} can be written as:

$$h_1 = h_4 + C_{pORC}\left(T_1 - T_4\right) + h_{lv}\left(T_1\right) \qquad (2)$$

$$h_{10} = h_6 - C_{pw}\left(T_6 - T_{10}\right) \qquad (3)$$

Substitution of equation (2) and (3) to (1) gives the balance of the evaporator in the form:

$$\dot{m}_{ORC}\left[C_{pORC}\left(T_1 - T_4\right) + h_{lv}\left(T_1\right)\right] = \dot{m}_w C_{pw}\left(T_6 - T_{10}\right) \qquad (4)$$

In equation (4) unknown are two quantities, namely temperature of heating fluid at outlet T_{10} and the ratio of flow rates of heating fluid and working fluid in ORC loop, namely m_w/m_{ORC}. The second equation, required to solve these two unknowns, is given by the heat balance of the fluid changing its parameters from inlet conditions corresponding to state 6 down to the pinch point:

$$\dot{m}_w^{'} C_p\left(T_6 - T_7\right) = \dot{m}_{ORC} h_{lv}\left(T_1\right) \qquad (5)$$

Expression (5) enables determination of the flow rate ratio m_w/m_{ORC} in function of evaporation temperature of working fluid in ORC installation and the minimum temperature, which can be determined from equation (5):

$$\Delta T_{\min} = T_7 - T_1 = \left(T_6 - T_1\right) - \frac{h_{lv}\left(T_1\right)}{\frac{\dot{m}_w^{'}}{\dot{m}_{ORC}} C_p} \qquad (6)$$

Heat supply to the ORC installation by means of the phase changing fluid

A similar analysis can be carried out for the case of the heat source in the form of a fluid which can change its phase during transfer of heat to the ORC installation. A schematic of such situation has been presented in Fig. 2.

The mean temperature drop in the evaporator will consist of three components, namely that corresponding to desuperheating of steam to reach saturation conditions, $LMTD_1$, its condensation, $LMTD_2$ and subcooling, $LMTD_3$. That is:

$$LMTD = \frac{LMTD_1 + LMTD_2 + LMTD_3}{3} \qquad (7)$$

The overall heat balance of the evaporator assumes a similar form to the balance presented in equation (1):

$$\dot{m}_{ORC}\left(h_1 - h_4\right) = \dot{m}_w\left(h_6 - h_{10}\right) \qquad (8)$$

The second equation used in the analysis is the heat balance down to the location where the pinch point occurs:

$$\dot{m}_{ORC}\left(h_1 - h_5\right) = \dot{m}_w\left(h_6 - h_9\right) \qquad (9)$$

It ought to be remembered that similarly as in the case of heating the ORC installation by means of the single phase fluid the transition from enthalpy h_4 to enthalpy h_1 by the working fluid consists first of heating the fluid to evaporation temperature T_1 followed by subsequent evaporation, hence enthalpy h_1 can be written as:

$$h_1 = h_4 + C_{pORC}(T_1 - T_4) + h_{lv}(T_1) \tag{10}$$

Enthalpy h_{10}, resulting from removing heat from the chase changing fluid from its inlet temperature T_6 to condensation temperature T_7, corresponding to pressure at temperature T_6, subsequent condensation to temperature T_8 and subcooling to T_{10} can be written as:

$$h_{10} = h_6 - C_{pv}(T_6 - T_7) - h_{lv}(T_7) - C_{pl}(T_8 - T_{10}) \tag{11}$$

Substitution of equations (10) and (11) to (8) returns:

$$\frac{\dot{m}_w}{\dot{m}_{ORC}}\left[C_{pv}(T_6 - T_7) + h_{lv}(T_7) + C_{pl}(T_8 - T_{10})\right] = \left[C_{pORC}(T_1 - T_4) + h_{lv}(T_1)\right] \tag{12}$$

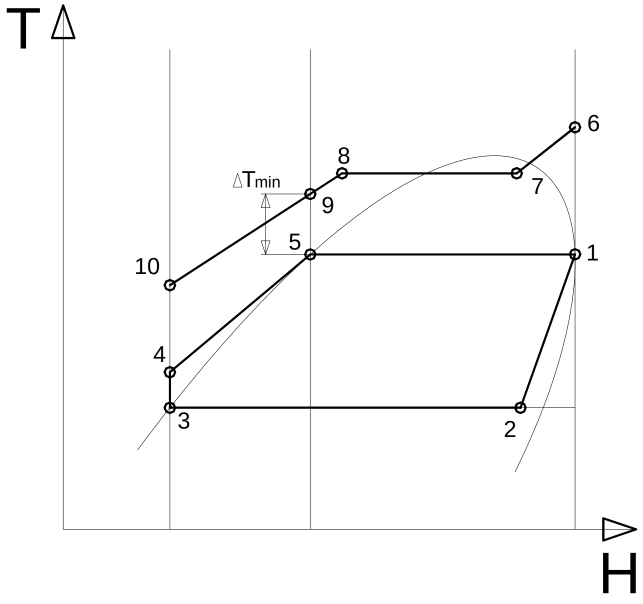

Figure 2 A schematic of heat supply to the ORC system by means of the fluid changing phase, H=m h

In equation (12) unknown are the values of outlet temperature of heating medium T_{10} and the ratio of mass flow rates m_w/m_{ORC}. In order to obtain the second equation enabling us determination of the two quantities we can write the heat balance equation for the heat carrier from the node 6 to the pinch point, by a correct casting of equation (9):

$$\frac{\dot{m}_w}{\dot{m}_{ORC}}\left[C_{pv}(T_6 - T_7) + h_{lv}(T_7) + C_{pl}(T_8 - T_9)\right] = h_{lv}(T_1) \tag{13}$$

Expression (13) enables determination of the minimum temperature difference at the pinch point:

$$\Delta T_{\min} = T_9 - T_1 = (T_8 - T_1) - \frac{\frac{\dot{m}_w'}{\dot{m}_{ORC}}\left[C_{pv}(T_6 - T_7) + h_{lv}(T_7)\right] - h_{lv}(T_1)}{\frac{\dot{m}_w'}{\dot{m}_{ORC}} C_p} \tag{14}$$

On the other hand, if we assume the temperature difference at pinch point then from equation (14) we can determine the unknown ratio m_w/m_{ORC}. Knowing that quantity enables simple determination of the outlet temperature of the heating fluid T_{10} in ORC installation.

In the considered case it is assumed that the location at which there is found the minimum temperature difference between the heating fluid and the ORC working fluid is on the liquid line of the heating fluid. In practice that point can be found also in the region of condensation. Such case can be relatively simply predicted by checking the condition

$$\Delta T_{\min} \geq (T_8 - T_1) \tag{15}$$

A CONCEPT OF REHEATING THE ORC SYSTEM

The new concept of using heat from the steam extraction is assumed to heat-up the working fluid in the ORC plant in two stages. As the work presented here is a part of the project aimed at utilisation of waste heat in the reference power plant in the manner to produce electricity in ORC installation therefore 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 ORC turbine. That was the incentive to search for the ways of increasing the temperature of the vapour at ORC turbine inlet. In authors opinion the steam from extraction point fits very well that idea. In this paper presented will be calculations with the rate of supplied waste heat in the amount of 10 MW to the ORC in the form of stream of hot water at 90^{0}C. Subsequently the steam from the extraction will be used in the specified fraction to raise further temperature of working fluid.

Waste heat, $\dot{Q}_{in1}$, see Figure 3, heats the working fluid from the state 4, if the cycle is without internal heat recovery, to the state marked on the diagram as the point 4’. The second stage of heating provides the heat supply, using for this purpose one of the streams of bleed steam from the steam turbine, $\dot{Q}_{in2}$, originally used to preheat the boiler feedwater, Fig. 3. Part of the stream of steam is routed to the ORC system to superheat the vapour from point 4’ to point 1.

In the present study it was assumed that temperature of working fluid vapour before the ORC turbine will be 120^{0}C. Remaining part of the steam from the extraction point is used for preheating of the boiler feedwater, Fig. 3. It must be remembered that the rate of heat directed to the feed-water heater will be smaller than that if the ORC is not present.

Diagram of ORC installation with connections to steam bleeds is shown in Figure 3. Only a portion of the steam stream is directed to the working fluid vapour heater (Heat Exchanger (HE) in Fig. 3) in the low-temperature ORC installation. The 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 temperature difference" between the hot fluid and working fluid, as shown in Fig. 4. It is our intention, that the waste heat is heating the working fluid between the states 4 and 4'. 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. If the heating medium for the ORC installation was not able to change phase then the temperature of vapour prior to the turbine would be much lower, or enthalpy of the heating fluid would not be sufficiently used.

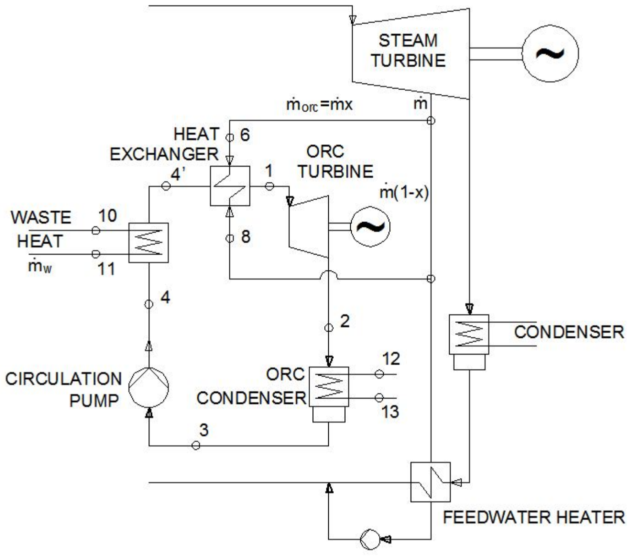

Figure 3 A general concept of heat supply to ORC installation with internal heat regeneration

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_{10}=90^{o}C. Following condensation and subcooling the liquefied steam is discharged to the feed water heat exchanger contributing to 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 feed water heat exchanger as originally envisaged.

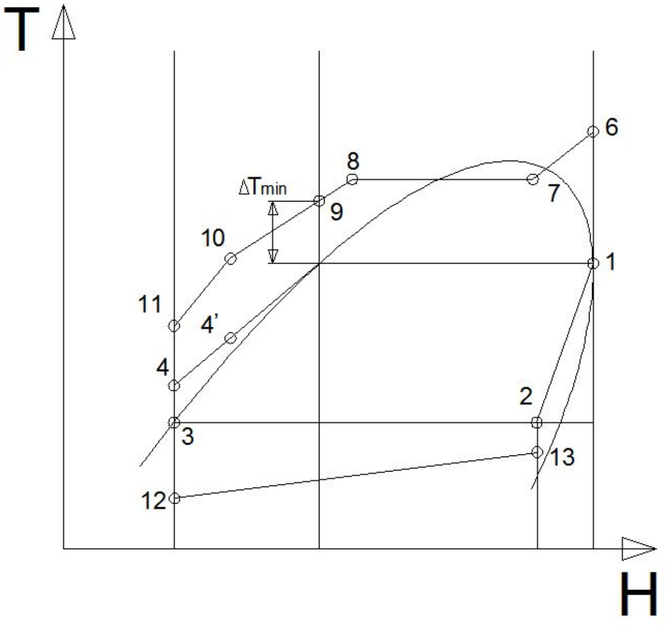

Figure 4 Cooperation of available heat sources with the ORC system, H – total fluid enthalpy

A general heat balance in the steam-working fluid HE has a similar form to that considered in case of equation (1):

$$\dot{m}_{ORC}(h_1-h_4)=\dot{m}_{w1}(h_6-h_{10})+\dot{m}_{w2}(h_{10}-h_{11}) \tag{16}$$

The second equation which is used in analysis is a heat balance from the inlet conditions to the pinch point. In the balance presented here it is assumed that it will be found following the complete condensation of bleed steam. Hence:

$$\dot{m}_{ORC}(h_1-h_5)=\dot{m}_{w1}(h_6-h_9) \tag{17}$$

It ought also to be remembered that similarily as in case of heating the ORC system using a single phase fluid then the transfer from enthalpy h_4 to enthalpy h_1 of the working fluid in ORC installation consists first of heating the working fluid to saturated liquid temperature T_1 and then its subsequent evaporation, hence enthalpy h_1 can be written as:

$$h_1=h_4+C_{pORC}(T_1-T_4)+h_{lv}(T_1) \tag{18}$$

Enthalpy h_{10}, resulting from cooling of the heating medium (bleed steam) from temperature T_6 to saturation temperature T_7, corresponding to pressure at temperature T_6, then vapour condensation to temperature T_8 and subcooling to T_{10} can be written as:

$$h_{10}=h_6-C_{pv}(T_6-T_7)-h_{lv}(T_7)-C_{pl}(T_8-T_{10}) \tag{19}$$

Substitution of equations (18) and (19) to (17) returns:

$$\frac{\dot{m}_{w1}}{\dot{m}_{ORC}}\left[C_{pv}(T_6-T_7)+h_{lv}(T_7)+C_{pl}(T_7-T_9)\right]=h_{lv}(T_1) \tag{20}$$

In equation (20) unknown are values of temperatures of heating fluid at pinch point T_9 as well as the ratio of mass flow rates of bleed steam to the flow rate of working fluid in ORC m_{w1}/m_{ORC}. From equation (20) we can determine temperature T_9 and then introducing the definition $\Delta T_{min}=T_9-T_1$ we determine the quantity m_{w1}/m_{ORC}, hence:

$$\frac{\dot{m}_{w1}}{\dot{m}_{ORC}}=\frac{h_{lv}(T_1)}{\left[C_{pv}(T_6-T_7)+h_{lv}(T_7)+C_{pl}(T_7-T_1-\Delta T_{min})\right]} \qquad (21)$$

Expression (20) enables determination of the minimum temperature difference at pinch point:

$$\Delta T_{min}=T_9-T_1=\frac{\frac{\dot{m}_{w1}'}{\dot{m}_{ORC}}\left[C_{pv}(T_6-T_7)+h_{lv}(T_7)+C_{pl}(T_7-T_1)\right]-h_{lv}(T_1)}{\frac{\dot{m}_{w1}'}{\dot{m}_{ORC}}C_{pl}} \qquad (22)$$

From equation (16) we can determine the secondo ratio of mass flow rates, hence m_{w2}/m_{ORC}.

$$\frac{\dot{m}_{w2}}{\dot{m}_{ORC}}=\frac{C_{pORC}(T_1-T_4)+h_{lv}(T_1)-\frac{\dot{m}_{w1}}{\dot{m}_{ORC}}\left[C_{pv}(T_6-T_7)+h_{lv}(T_7)+C_{pl}(T_7-T_{10})\right]}{C_{pl}(T_{10}-T_{11})} \qquad (23)$$

We assume that parameters of waste heat fluid at outlet is known, i.e. T_{10}. In relation to that either we can determine the second ratio of mass flow rates, i.e. m_{w2}/m_{ORC} or the outlet temperature of heating fluid. Examples of calculation of respective ratios of mass flow rates is presented in Fig. 5 and 6.
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 evaporation temperature of working fluid is assumed as 120^0C whereas in case when ORC system has no extra input of heat then the corresponding evaporation temperature of working fluid is assumed at 80^0C, 70^0C, 60^0C and 50^0C. The condensation temperature has been assumed at two levels, i.e. 40^0C and 10^0C, corresponding to summer and winter conditions. Analysis of Fig. 6 exhibits that for small ΔT_{min}=5K there is a five fold greater amount of waste heat flow rate required. For highest evaporation temperature that means that utilization of that heat is small, the outlet temperature of waste heat medium is only 84.5°C, see Table 5.

The efficiency of the reference electricity generation plant if no steam is taken for supplying the ORC installation is η_b=49.1%. If some steam from the bleed is taken to aid the ORC installation that overall efficiency is to decrease.

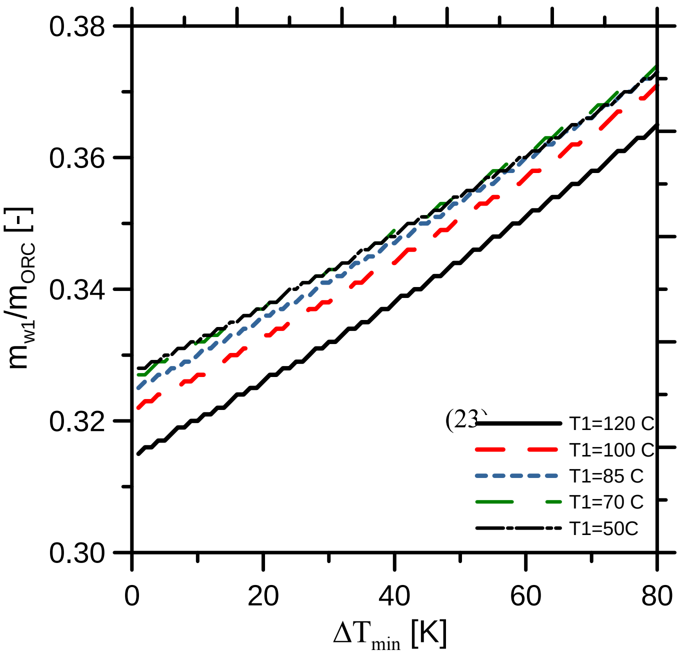

Figure 5 Ratio of mass flow rates of bleed steam to the working fluid m_{w1}/m_{ORC} in function of pinch temperature for different evaporation temperatures of ethanol evaporation and inlet temperature of waste heat flow rate equal T_6=90°C.

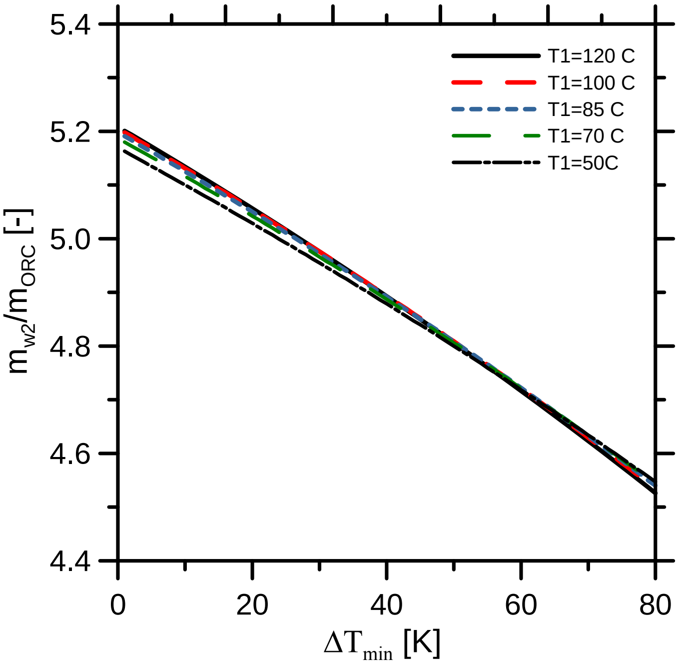

Figure 6 Ratio of mass flow rates of waste heat fluid to the working fluid m_{w2}/m_{ORC} in function of pinch temperature for different evaporation temperatures of ethanol evaporation and inlet temperature of waste heat flow rate equal T_6=90°C.

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, MM, MDM, and toluene. The software REFPROP version 9.0 [6] was used for the calculations of thermal properties. MM and MDM are representatives of silicone oils, so called linear dimethylsiloxanes, widely used in ORC, Table 1. Presented below is the calculation procedure for ORC system efficiency:

1. Turbine power: $P_T = \dot{m}_{ORC}(h_1 - h_2)$
2. Generator power $P_G = P_T \eta_G$
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 $P_P = \dfrac{\dot{m}_{ORC}(h_4 - h_3)}{\eta_P}$
6. Efficiency without regenerator $\eta_{ORC} = \dfrac{P_T - P_P}{\dot{Q}}$

Table 1.

Characteristic data of considered working fluids

Fluid	M	p_{cr}	T_{cr}
	kg/kmol	bar	°C
Toluene	92.138	41.26	318.60
MDM	236.53	14.15	290.94
C_2H_5OH	46.00	61.48	240.75
MM	162.38	19.39	245.60
R134a	102.03	40.59	101.06

Presented in Table 2 are the values of key parameters in the characteristic points of the organic Rankine cycle for different working fluids.

Table 2

Values of parameters in the characteristic points of the vapour superheater

Node no.	t [°C]	p [bar]	h[kJ/kg]	m [kg/s]
6	228.8	2.519	2926.7	23.03
8	90.0	2.519	377.18	23.03
4’	80.0	1.0857	1267.0	5.34/4.79
1	120.0	1.0857	1342.3	5.34/4.79

Table 3 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.

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, as is necessary in the case o toluene and silicone oils, considered here. 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.

Table 3.

*ORC 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	0.137
Ethanol	0.090	0.153	0.093	0.156
MM	0.079	0.129	0.072	0.121
	0.089*	0.152*	0.092*	0.168*
MDM	0.078	0.126	0.007	0.117
	0.089*	0.152*	0.090*	0.167*
Toluene	0.088	0.148	0.088	0.151
			0.099*	0.165*

If we assume $Q_{in\ 1}$=10MW of heat supplied in such way than we can determine the flow rate of working fluid in the ORC installation from (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: 10.7kg/s for the conditions of 120/40°C and 9.58 for 120/10°C , respectively. The source of bleed steam contains 23.03kg/s of steam, which means that about 40% of available flowrate will be directed to the ORC installation.

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, as shown in Figure 3. Mass flow rate of organic fluid increases its enthalpy from point 4’ to point 1. In the second leg of the heat exchanger the bleed steam changes its enthalpy from the point 8 to 9. We assume that the steam will be desuperheated, condensed and subsequently subcooled, as shown in Fig. 4. Results are presented in Table 4.

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^{o}C and subcooled to 90^{o}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 directed from a bleed steam to organic fluid to obtain its desired temperature equal to 120^{o}C.

$$\dot{m}_{ORC}\left(h_1-h_d\right)=\dot{m}_u\left(h_6-h_8\right) \tag{25}$$

Equation (25) enables determination of the flow rate of bleed steam in aiding the ORC system. In effect for the conditions of 120/40^{o}C the flow rate of steam used in the ORC is 0.32kg/s, whereas for 120/10^{o}C it is 0.28kg/s, respectively.

Due to supply of heat from the bleed the ORC system gets additional thermal power, calculated as:

$$\dot{Q}_{in2}=\dot{m}_{bleed}\left(h_6-h_8\right) \tag{26}$$

The heat input to steam-working fluid heat exchanger at different working conditions of 120/40°C (summer) and 120/10°C (winter) is equal to 803.68kW and 719.86kW.
The total thermal power Q_{ORC}, is the sum of the thermal power supplied from waste heat and heat input Q_d from the bleed steam Q_u.

$$\dot{Q}_{ORC}=\dot{Q}_{in1}+\dot{Q}_{in2} \tag{27}$$

The total thermal power supplied to ORC is 10 803.68kW for the temperature conditions 120/40^{o}C and 10 719.86kW for 120/10^{o}C, respectively. On that basis the power generated in the ORC can be calculated from the formula:

$$N_e=\eta_{ORC}\dot{Q}_{ORC}=\eta_{ORC}\left(\dot{Q}_{in1}+\dot{Q}_{in2}\right) \tag{28}$$

The net amount of generated power is 1000.42kWe under conditions of 120/40^{o}C and 1675.52kWe under conditions 120/10^{o}C, respectively. Thermal power removed from the reference power plant Q_w for aiding the ORC is respectively 803.68kW for 120/40^{o}C and 719.86kW for 120/10^{o}C, respectively. The thermal power of the reference plant, Q, is calculated from the knowledge of the efficiency of electricity generation of that plant η_b=0.491 and the gross electric output of N_T=900 MWe. Therefore $Q=N_T/\eta_b$=1833.0MW.
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:

$$N_T^{'}=\eta_b\left(\dot{Q}-\dot{Q}_{in2}\right) \tag{29}$$

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.

Presented there are also the results of calculations for the case where ORC installation is regarded as a stand alone unit, which means that it is not utilising the heat from the extraction point and uses only the waste heat $Q_{in\ 1}$. In this case situation is a little bit complex. We must remember that we are dealing with a single phase source of waste heat medium. In order to supply 5MW of heat into the ORC working fluid we must ensure that there is preserved a minimum 5K pinch temperature between the heating fluid and working fluid. That means that either the flow rate of hot water will be very 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, $m_{w,}$ 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:

$$\dot{m}_w^{'}C_p\left(T_6-T_{pinch}\right)=\dot{m}_{ORC}h_{lv}\left(T_1\right) \tag{30}$$

Expression (30) enables calculation of the function of m_w/m_{ORC} in function of evaporation temperature of working fluid in ORC installation and minimum pinch temperature from:

$$\Delta T_{\min}=T_{pinch}-T_1=\left(T_6-T_1\right)-\frac{h_{lv}\left(T_1\right)}{\frac{\dot{m}_w^{'}}{\dot{m}_{ORC}}C_p} \tag{31}$$

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

Case	Power [kWe]
ΔN_{T1} (120/40^{o}C)	394.6
ΔN_{T1} (120/10^{o}C)	353.2

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

		Waste water inlet temperature/boiling temperature T_1			
		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	432.58	147.0	89.74	65.10
Electrical power of ORC	kW	1105.32	851.80	584.22	133.7
Waste water outlet temperature T_{11}	^{o}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^{o}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 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.

Table 6.

Comparison of the results of calculations.

		ORC with steam from extraction	
		120/40	120/10
Efficiency	-	0.093	0.156
Mass flow rate in ORC	kg/s	10.70	9.58
Mass flow rate from bleed	kg/s	1.945	1.86
Electrical power of ORC	kW	1000.42	1675,52
Power lost in reference plant	kW	394.6	353.2

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 Table 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.

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 installation. 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. The task undertaken was to best utilize the stream of hot water with temperature of 90°C. Majority of studies regard the upper heat source as the one with infinite heat capacity which is a rather non-practical assumption. In such case the heat is not utilized. In the paper it has been shown to what extent the waste heat can be used in reference to evaporation temperature in the ORC installation. It results from the study that either a high mass flow rate of heat supplying fluid is used or temperature before the turbine must the decreased. A mathematical model enabling calculations of such cases was presented. Condensing steam from extraction point fits better to the characteristics of the evaporation of working fluid in ORC installation.

Calculations have been accomplished for the case when available is a flow rate of hot water at a temperature of 90°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°C/40°C the silicone oil MM showed the best performance, in all other cases the ethanol proved to be best.

The use of waste heat at a temperature of 90°C in the ORC system with ethanol as working fluid seems to have great potential. In case of the evaporation 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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