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Influence of working fluid evaporation temperature in the near-critical point region on the effectiveness of ORC power plant operation

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Abstract In the paper presented are definitions of specific indicators of power which characterize the operation of the organic Rankine cycle (ORC) plant. These quantities have been presented as function of evaporation temperature for selected working fluids of ORC installation. In the paper presented also is the procedure for selection of working fluid with the view of obtaining maximum power. In the procedure of selection of working fluid the mentioned above indicators are of primary importance. In order to obtain maximum power there ought to be selected such working fluids which evaporate close to critical conditions. The value of this indicator increases when evaporation enthalpy decreases and it is known that the latent heat of evaporation decreases with temperature and reaches a value of zero at the critical point.

Keywords: ORC; Binary power plants; Near-critical region; Working fluid

Nomenclature

A – heat transfer surface
c – specific heat, kJ/kgK
h – specific enthalpy, kJ/kg
l – specific work, kJ/kg

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N – power, kW
$\dot{m}$ – flow rate, J/kg
q – specyfic heat flow rate, kg/s
q_N – specyfic indicator
$\dot{Q}$ – total heat flow rate, kW
T – temperature, °C

Subscripts

$C-R$ – Clausius-Rankine cycle
d – supplied
g – geothermal water
n – organic fluid
s – network water
$c-e$ – condenser-evaporator heat exchanger
w – water in upper cycle
1, 2s, 3, 4s, 5 – characteristic points of cycle

Superscripts

L – lower cycle of binary power plant cycle
U – upper cycle of binary power plant cycle
$cond$ – condensation
$evap$ – evaporator
$preh$ – preheater

1 Introduction

In the paper presented are definitions of two specific indicators of power which characterize operation of the organic Rankine cycle (ORC) plant. These quantities have been presented as function of evaporation temperature for selected working fluids of ORC installation in the form of tables and diagrams in the following pattern:

$$q_N^{evap} = f(\text{kind of fluid}, T_{evap}) \, , \tag{1}$$

$$q_N^{preh} = f(\text{kind of fluid}, T_{evap}) \, . \tag{2}$$

In the paper presented also is the procedure for selection of working fluid with the view of obtaining maximum power. In the procedure of selection of working fluid the mentioned above indicators and are of primary importance.

In accomplished considerations the assumption was made that the amount of supplied energy with the heat carrier is the same no matter which location in the considered cycle it is supplied. Presented considerations are related to geothermal power plant operation for different configurations of

ORC. These configurations encompass a single-loop ORC installation and a binary plant, where in the lower cascade the organic fluid is used as working fluid.

2 Case I – Single-loop power plant

In Fig. 1 presented is a single-loop schematic of ORC supplied with water as a heat carrier with a known flow rate $\dot{m}_s$ and temperature T_{s1}.

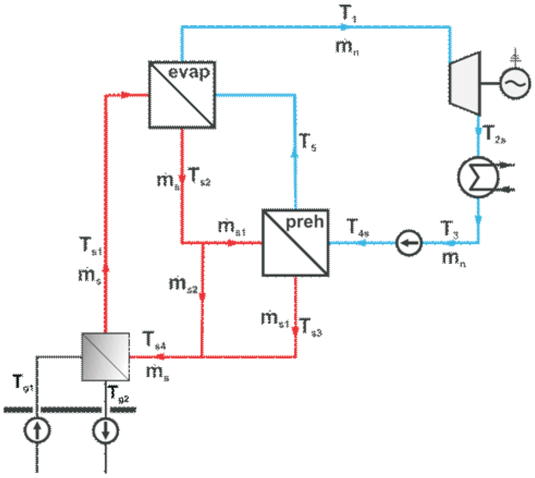

Figure 1. A single-loop schematic of ORC (evap – evaporator, preh – preheater).

Water with reduced temperature which leaves the evaporator is splitted into two flow rates, namely $\dot{m}_{s1}$ and $\dot{m}_{s2}$. The first one is directed to the heater of working fluid, whereas the second one, which is a surplus of the flow rate required in the heater (being the difference between the flow rate $\dot{m}_s$ and the flow rate $\dot{m}_{s1}$), is directed to a special bypass after the heater. The flow rate $\dot{m}_{s1}$, following the energy transfer in the heater to the organic working fluid, is subsequently reconnected with the flow rate $\dot{m}_{s2}$. Next, the total flow rate of water $\dot{m}_s$ having temperature T_{s3} is directed to the geothermal heat exchanger, where geothermal water flowing in counter-current provides its heating to the required temperature T_{s1}.

The power plant presented in Fig. 1 operates according to the Clausius-Rankine comparative thermodynamical cycle. The processes realized in that cycle are presented in the pressure-enthalpy diagram $(p-h)$ in Fig. 2. That cycle consists of two isobars, namely the top isobar during which heat

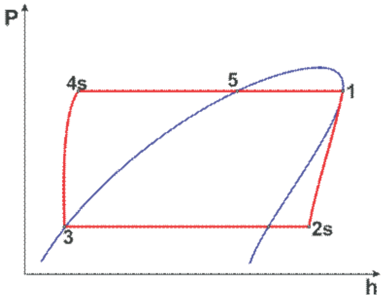

Figure 2. The cycle of thermodynamical processes in the C-R cycle for low boiling point fluids from group I.

supply process from the upper heat source takes place, and a lower one, during which heat is removed from the cycle to the lower heat reservoir. In the paper it has been assumed that the transition between these two isobars is isentropic. A precise description of operation of a single-loop power plant featuring evaporator with internal circulation and the algorithm of calculations has been presented in [1]. Presented below are merely the most important relations used in calculations.

Specific power of the power plant:

$$l_{C-R} = (h_1 - h_{2s}) - (h_{4s} - h_3) \ . \tag{3}$$

Specific rate of heat supplied in the heater:

$$q_{preh} = h_5 - h_{4s} \ . \tag{4}$$

Specific rate of heat supplied in the evaporator:

$$q_{evap} = h_1 - h_5 \ . \tag{5}$$

Total specific heat supplied to Clausius-Rankine cycle:

$$q_d = q_{preh} + q_{evap} = h_1 - h_{4s} \ . \tag{6}$$

Specific rate of heat removed from the condenser is determined by relation (the process consists of desupeheating and condensation of organic fluid vapour):

$$q_w = q_{cond} = h_{2s} - h_3 \ . \tag{7}$$

The relation for the mass flow rate of organic fluid circulating in the Clausius-Rankine cycle can be determined from the energy balance for the evaporator neglecting the heat losses and reads as follows:

$$\dot{m}_n = \frac{\dot{Q}_{evap}}{h_1 - h_5} \tag{8a}$$

or

$$\dot{m}_n = \dot{m}_s \frac{c_s\left(T_{s1} - T_{s2}\right)}{\Delta h_{evap}} \ , \tag{8b}$$

where Δh_{evap} is the enthalpy of evaporation. Power of the Clausius-Rankine cycle can be determined from the relation

$$N_{C-R} = \dot{m}_n l_{C-R} \ , \tag{9}$$

or considering Eq. (6) in the form

$$N_{C-R} = \frac{\dot{Q}_{evap}}{\Delta h_{evap}} l_{C-R} \ . \tag{10}$$

Introducing the specific indicator of power

$$q_N^{evap} = \frac{l_{C-R}}{\Delta h_{evap}} \tag{11}$$

the relation (10) assumes the following form:

$$N_{C-R} = \dot{Q}_{evap}\, q_N^{evap} \ . \tag{12}$$

It stems from relation (12) that at the same rate of supplied heat to the evaporator, $\dot{Q}_{evap}$, the working fluid featuring the highest indicator of power should be selected from the point of view maximum power.

In Fig. 3 presented is the temperature distribution of heat exchanging fluids in the evaporator.

3 Case II – Binary power plant

In the temperature-entropy (T-S) diagram (Fig. 4) presented is the cycle of thermodynamic processes accomplished in the binary power plant. Description of such type of the power plant, way of its operation and algorithm of calculations has been presented in [2,3], whereas presented below are only

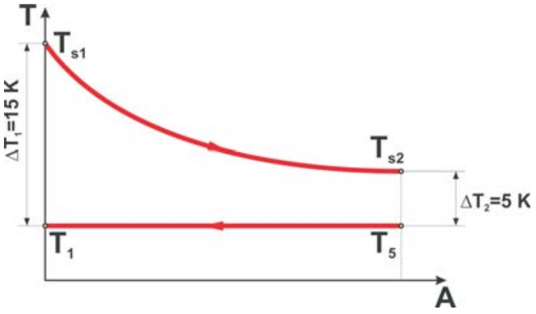

Figure 3. Temperature distributions of heat exchanging fluids in evaporator.

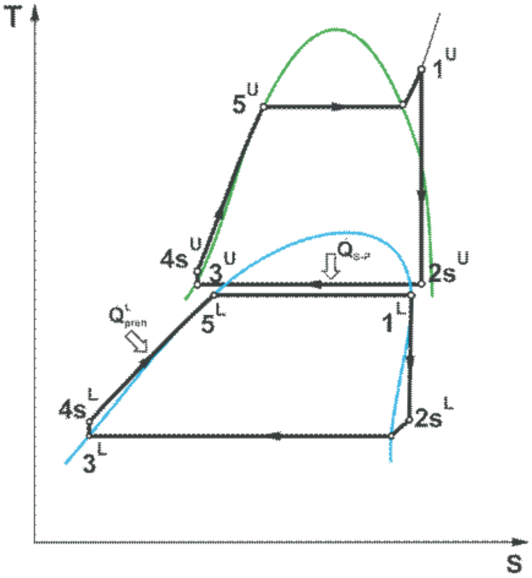

Figure 4. Cycle of thermodynamic processes of the upper and lower cascade of binary power plant.

the expressions which are indispensable for definition of relevant specific indicators of power.

Considerations relating to the binary power plant have been carried out for two subcases, which are different from each other from the point of view of starting parameters in the calculation algorithm:

- Subcase A, when calculations of the binary power plant are carried out at the assumption that known are the parameters of superheated steam in the upper cascade of binary plant as well as the flow rate of water as a working fluid in the upper cascade.

- Subcase B, where the starting point for calculations of binary power plant is the rate of heat, $\dot{Q}^L_{preh}$, supplied in the heater to the working fluid of the lower cascade.

3.1 Subcase A

The basis of calculations of the mass flow rate of working fluid in the lower cascade is the relation presented below, which results from the energy balance equation for the condenser-evaporator heat exchanger. That relation for its calculation which neglects the heat losses to surroundings assumes the following form:

$$\dot{m}_n^L = \frac{\dot{Q}_{c-e}}{h_1^L - h_5^L} = \dot{m}_p^U \frac{h_{2s}^U - h_3^U}{\Delta h_{evap}^L} \,. \tag{13}$$

The power is determined from the expression

$$N_{C-R}^{LA} = \dot{m}_n^L \; l_{C-R}^L \,. \tag{14}$$

After introduction of relation describing the specific power indicator

$$q_N^{evap\,L} = \frac{l_{C-R}^L}{\Delta h_{evap}^L} \tag{15}$$

and considering relation (13) the expression for the power takes the form

$$N_{C-R}^{LA} = \dot{Q}_{c-e}\, q_N^{evap\,L} \,. \tag{16}$$

It stems from Eq. (16) that at the same rate of heat supplied to the lower cascade $\dot{Q}_{c-e}$ there ought to be selected the working fluid featuring the highest value of the specific power indicator $q_N^{evap\,L}$ if maximum power is sought.

3.2 Subcase B

Another specific power indicator is valid in the case where the starting point for calculation of the binary power plant is the rate of heat $\dot{Q}^L_{preh}$ supplied in the heater to the working fluid of the lower cascade. In considerations it has been assumed that the heater is a counter-current heat exchanger where there is obeyed the condition of equal rates of heat capacity of both heat carriers, namely of water and working fluid.

Energy balance equation for the case of the heater, neglecting the heat losses to surroundings, can be written in the form

$$\dot{Q}^L_{preh} = \dot{m}^L_s c_s \left(T^L_{s1} - T^L_{s2}\right) = \dot{m}^L_n \left(h^L_5 - h^L_{4s}\right) . \tag{17}$$

From relation (17) there can be obtained an expression enabling determination of the mass flow rate of working fluid in the lower cascade:

$$m^L_n = \frac{\dot{Q}^L_{preh}}{\Delta h^L_{preh}} . \tag{18}$$

The extent of power of the lower cascade of the binary power plant is determined by relation

$$N^{LB}_{C-R} = m^L_n \; l^L_{C-R} . \tag{19}$$

Incorporating the specific indicator of power $q_N^{preh\,L}$ defined as

$$q_N^{preh\,L} = \frac{l^L_{C-R}}{\Delta h^L_{preh}} , \tag{20}$$

where Δh_{prev} is the ???? and considering expressions (17) and (18) then the relation (19) is finally assuming the following form:

$$N^{LB}_{C-R} = \dot{Q}^L_{preh} \, q_N^{preh\,L} . \tag{21}$$

It stems from Eq. (21) that at the same rate of heat supplied in the heater, $\dot{Q}^L_{preh}$, the higher power of the lower cascade can be obtained for the fluid featuring a higher value of the specific power indicator $q_N^{preh\,L}$.

Presented below are the examples illustrating values of that indicator for different working fluids of the lower cascade. Following introduction of the parameter defined as

$$q_{p,e} = \frac{q_{preh}}{q_{evap}} . \tag{22}$$

It can be shown that the relation between specific indicators of power q_N^{preh}, q_N^{evap} and a parameter specified by expression (22) is found in the following form:

$$q_N^{evap} = q_N^{preh} \; q_{p,e} . \tag{23}$$

4 Results of calculations

In all presented in the paper results of calculations regarding the ORC power plant (case I and the lower cascade of binary power plant of case II) there has been assumed that evaporation temperature of the working fluid is 101 °C whereas the condensation temperature is 29 °C, respectively. The considerations presented in the paper regard the following working fluids, namely R245ca, R142b, perfluoropentane and perfluorobutane, for which the specific indicators of power have been specified, namely q_N^{preh}, q_N^{evap} and the parameter $q_{p,e}$.

In case I, the ORC power plant is supplied with water having temperature (at the inlet to evaporator) equal to 116 °C and a flow rate of water equal to $\dot{m}_s = 1$ kg/s, to which corresponds the rate of heat supplied in the evaporator in the amount of $\dot{Q}^I_{evap} = 43$ kW. In case II the ORC is realized as a lower cascade of the binary power plant. In subcase A considered have been parameters of the upper cascade where water serves as a working fluid being circulated with the flow rate of $\dot{m}_p^U = 1$ kg/s. Parameters of superheated steam are respectively equal to: $T_1 = 380$ °C, and $p_1 = 18$ MPa, whereas condensation temperature is 104 °C. The power resulting from the presented above parameters is $N^U_{C-R} = 660$ kW and the flow rate of water removed in the condenser-evaporator type of heat exchanger is $\dot{Q}^U_w = Q^U_{c-e} = 1570$ kW. On the basis of the latter quantity determined have been the available powers for considered working fluids N^{LA}_{C-R}. In the subcase B of the binary power plant it has been assumed that the rate of heat supplied in the counter-flow heater is known as well as the rates of heat capacity of water and liquid phase of working fluid are equal. It has been assumed that temperature of supplied water T_{s1} is 104 °C and the flow rate of water supplying heat is $\dot{m}_s^{LB} = 1$ kg/s. In that heat exchanger liquid phase of working fluid is heated from the condensation temperature to the evaporation temperature and the rate of removed heat for considered working fluids is 298 kW.

In line with the calculation algorithm and the above description determined has been the power of the single-loop plant N_{C-R} as well as power of lower cascades for the subcases of the binary power plant N^{LA}_{C-R} and N^{LB}_{C-R}. Selected results of calculations have been presented in Tab. 1.

Table 1. Tabulation of specific indicators together with other quantities characterizing operation of ORC plant.

Working fluid	l_{C-R}	q_{evap}	q_{preh}	q_N^{evap}	q_N^{preh}	$q_{p,e}$	$\dot{m}_s$	N_{C-R}	$\dot{m}_n^{LA}$	N_{C-R}^{LB}	$\dot{m}_n^{LA}$	N_{C-R}^{LB}
R245ca	39.5	150.6	103.0	0.26	0.38	0.68	0.28	11.3	10.42	411.8	2.89	114.3
R142b	36.1	129.4	103.7	0.28	0.35	0.80	0.33	12.0	12.13	438.5	2.87	103.9
Perfluoro-pentane	18.7	63.2	83.2	0.30	0.22	1.32	0.68	12.7	24.83	465.1	3.58	67.1
Perfluoro-butane	16.1	39.7	87.6	0.40	0.18	2.21	1.08	17.4	39.54	635,0	3.40	54.6

5 Concluding remarks

On the basis of concluded analysis of obtained results the following conclusions can be drawn:

- If the initial assumption for the analysis is the value of the rate of heat supplied to evaporator of ORC plant (case I and subcase A) then the specific power indicator q_N^{evap} is a criterion for the selection of the appropriate working fluid with the view to maximize power; higher values of that indicator correspond to higher values of power.
- In case when the initial assumption for the analysis is the value of the rate of heat supplied to the heater of the working fluid (subcase B) then as a criterion for the selection of working fluid the specific power indicator q_N^{preh} ought to be used; higher values of that indicator correspond to higher values of power of ORC plant.
- In the first case in order to obtain maximum power there ought to be selected such working fluids which evaporate close to critical conditions. In line with relation (15) the value of indicator q_N^{evapL} increases when evaporation enthalpy decreases and it is known that the latent heat of evaporation decreases with temperature and reaches a value of zero at the critical point.

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