INFLUENCE OF SUPERHEATED STEAM TEMPERATURE IN THE UPPER CASCADE OF THE BINARY POWER PLANT WITH A LOW-BOILING POINT FLUID IN THE LOWER CASCADE ON THE EFFECTIVENESS ITS OPERATION

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Abstract

In the paper a comparative assessment of two cases of a power plant has been conducted using relevant mathematical models, that is of a steam plant supplied with energy from a fossil fuel and a low-temperature waste energy as well as a binary power plant with water and organic substance as working fluids also supplied with energy from fossil fuels and co-supplied with low-temperature energy. Calculations of capacity and efficiency of both power plants have been accomplished at the assumption of a constant value of a rate of energy supplied with the fuel and comparative operational conditions in all considered cases.

KEYWORDS

Geothermal power plant, binary power plant, Organic Rankine Cycle (ORC)

INTRODUCTION

The starting point for the analysis of the effectiveness of operation of different designs of power plants is a single fluid power plant with superheating, where the water is a working fluid. Such power plant has been replaced with a binary power plant operating in the same temperature range of upper and lower heat reservoir. Heat transfer in a binary power plant from the upper cascade to the lower one takes place in the heat exchanger of the condenser-evaporator type.

In the paper presented are schematics of both power plants which operate in line with the comparative Clausius-Rankine cycle. Presented also have been algorithms of calculations considering such quantities as rates of supplied and removed heat together with a power and efficiency of respective cycles. Calculations were performed for selected organic fluids operating in the lower cascade. The results of calculations have been presented in a form of diagrams enabling comparative assessment of a binary cycle with a single loop cycle, which subsequently led to final conclusions.

STEAM POWER PLANT (reference case)

A steam power plant (reference case), a schematic of which is presented in figure 1, is supplied with heat from two heat sources. A principal source of heat is a conventional boiler for superheating of steam, evaporation and heating of a working fluid in the higher temperature range. Heating of a fluid in the lower temperature range is realized through energy supplied with a low-temperature heat carrier in additional heat exchanger.

Algorithm for calculations of steam plant (reference case)

Rate of heat supplied to the cycle (Fig. 2) with the view of heating and evaporation of water and its superheating is determined by the relation:

$$\dot{Q}_d^P = \dot{Q}_{dodp}^P + \dot{Q}_{dk}^P = \dot{m}_p\left(h_5^{P*} - h_4^P\right) + \dot{m}_p\left(h_1^P - h_5^{P*}\right) \tag{1}$$

where $\dot{Q}_{dodp}^P$ – rate of heat transferred to water in a low-temperature heat exchanger,

$\dot{Q}_{dk}^P$ – rate of heat which need to be supplied in a steam boiler.

Superheater

Steam turbine

Steam boiler

Generator

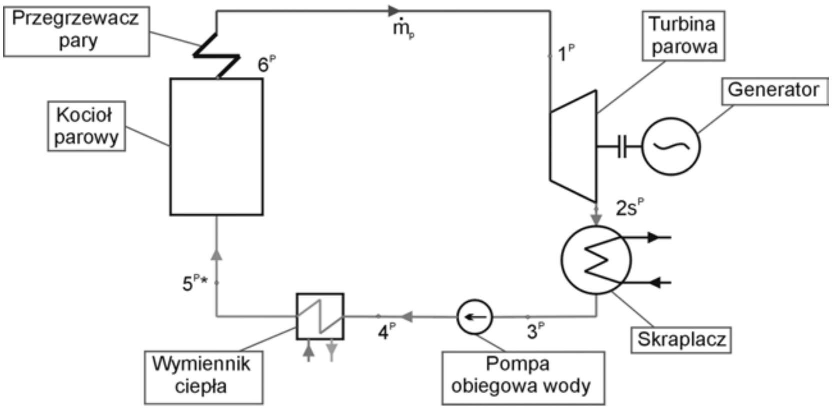

Fig. 1. Schematic of a steam plant „reference case” with a boiler supplied with energy from combustion of fossil fuels and co-supplied with low-temperature waste energy

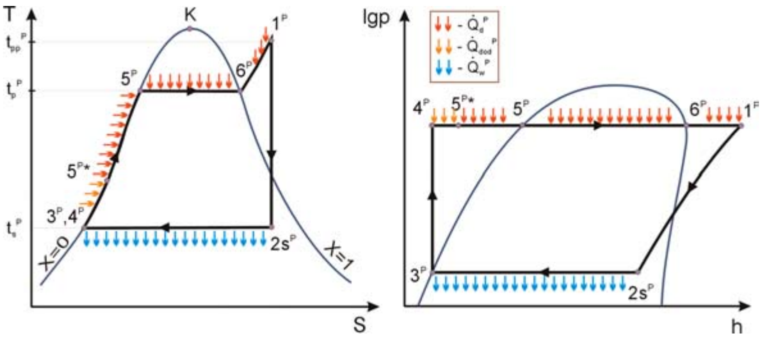

Fig. 2. Sequence of thermodynamical processes in a reference power plant

The rate of heat removed from the cycle in a condenser has been calculated from relation:

$$\dot{Q}_w^P = \dot{m}_p \left(h_{2s}^P - h_3^P \right). \tag{2}$$

For calculation of the power of the Clausius-Rankine cycle a relation can be used which utilizes the adiabatic enthalpy change in a turbine:

$$N_{C-R}^P = \dot{m}_p \left(h_1^P - h_{2s}^P \right). \tag{3}$$

The efficiency of the Clausius-Rankine cycle has been found from relation:

$$\eta_{C-R}^P = \frac{N_{C-R}^P}{\dot{Q}_d^P} = 1 - \frac{\dot{Q}_w^P}{\dot{Q}_d^P}. \tag{4}$$

The rate of low-temperature heat carrier (for example of geothermal water) used for heating of working fluids in the enthalpy range from h_4 to h_5^{P*} can be determined from relation:

$$\dot{Q}_{dodp}^{P*} = \dot{m}_p \left(h_5^{P*} - h_4^P \right) = \dot{m}_{odp} c_{podp} \left(T_{odp1} - T_{odp2} \right) \tag{5}$$

bearing in mind that h_5^{P*} is dependent on T_{odp1}.

BINARY POWER PLANT

The binary power plant (Fig. 3) consists of an upper cascade, where the water is a working fluid and a lower cascade, where a selected organic substance is a working fluid.

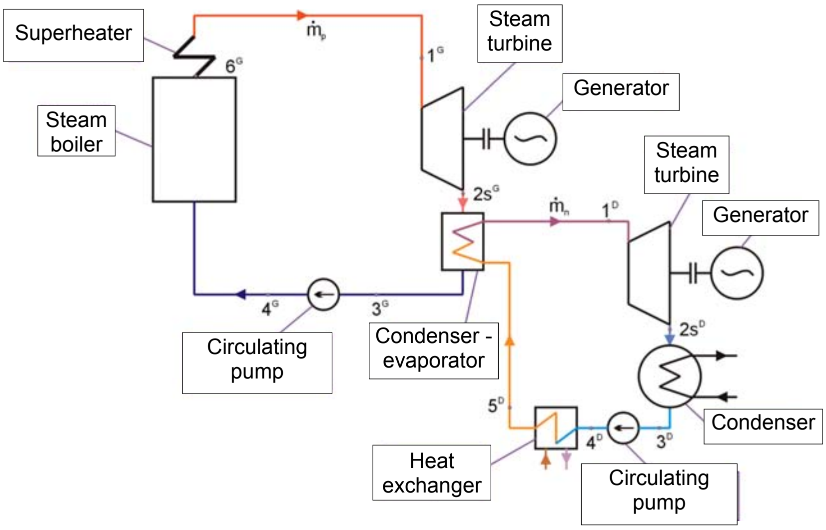

Fig. 3. Schematic of a binary power plant supplied with energy in boiler and co-supplied with low temperature waste energy

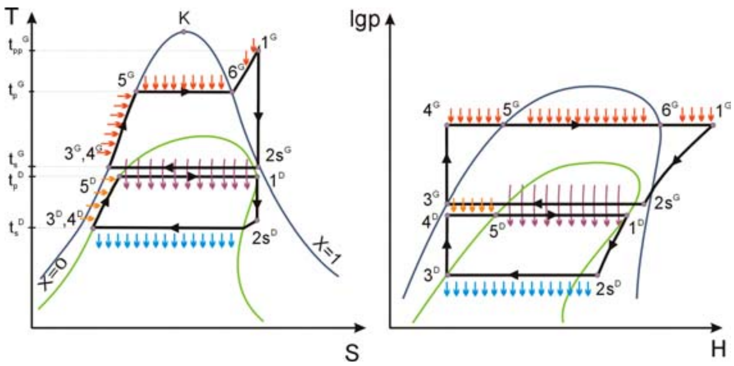

Fig. 4. Sequence of thermodynamical processes in a binary power plant

Water is a so called wet fluid, which in relation to the assumptions on realisation of steam power cycle should be superheated to a small or greater extent before entering the turbine. Selected organic fluids represent a group of so called dry fluids, in the case of which the superheating process is not required and in many cases even not recommended.

An upper cascade is supplied in total with energy obtained from combustion of fuel in a boiler, whereas the lower cascade is partially supplied with energy from a boiler and co-supplied with a low-temperature energy.

Algorithm of calculations of a upper cascade

The total rate of heat supplied to the upper cascade:

$$\dot{Q}_d^G = \dot{m}_p^G \left(h_1^G - h_4^G\right). \tag{6}$$

The rate of heat removed from the cycle in the condenser-evaporator type of heat exchanger:

$$\dot{Q}_w^G = \dot{Q}_{s-p} = \dot{m}_p^G \left(h_{2s}^G - h_3^G\right). \tag{7}$$

The power of a higher cascade (at the assumption of adiabatic drop of enthalpy in turbine) yields:

$$N_{C-R}^G = \dot{m}_p^G \left(h_1^G - h_{2s}^G\right). \tag{8}$$

The efficiency of the Clausius-Rankine cycle is:

$$\eta_{C-R}^G = \frac{N_{C-R}^G}{\dot{Q}_d^G} = 1 - \frac{\dot{Q}_w^G}{\dot{Q}_d^G}. \tag{9}$$

An element linking the upper and lower cascades (in line with figures 3 and 4) is a heat exchanger of the condenser-evaporator type, in the case of which the energy balance reads:

$$\dot{Q}_{s-p} = \dot{m}_p^G \left(h_{2s}^G - h_3^G\right) = \dot{m}_n^D \left(h_1^D - h_5^D\right). \tag{10}$$

From equation (10) the rate of working fluid in the lower cascade can be determined as:

$$\dot{m}_n^D = \dot{m}_p^G \left(h_{2s}^G - h_3^G\right) / \left(h_1^D - h_5^D\right). \tag{11}$$

Algorithm of calculations of a lower cascade

The total rate of heat supplied to the lower cascade is consisting in the rate of heat supplied in a heat exchanger supplied with low-temperature heat carrier from the waste energy (for heating of a low-boiling point fluid) and a rate of heat supplied in a heat exchanger of the condenser-evaporator type (used for evaporation of a low-boiling point fluid):

$$\dot{Q}_d^D = \dot{Q}_{s-p} + \dot{Q}_{dodp}^D = \dot{m}_n^D \left(h_5^D - h_4^D\right) + \dot{m}_n^D \left(h_1^D - h_5^D\right). \tag{12}$$

The rate of heat removed in a condenser is described by a relation:

$$\dot{Q}_w^D = \dot{m}_n^D \left(h_{2s}^D - h_3^D\right). \tag{13}$$

The power of a lower cascade (at the assumption of adiabatic enthalpy drop in turbine):

$$N_{C-R}^D = \dot{m}_n^D \left(h_1^D - h_{2s}^D\right). \tag{14}$$

The efficiency of the Clausius-Rankine cycle for the lower cascade reads:

$$\eta_{C-R}^D = \frac{N_{C-R}^D}{\dot{Q}_d^D} = 1 - \frac{\dot{Q}_w^D}{\dot{Q}_d^D}. \tag{15}$$

Algorithm of calculations of a binary power plant

The rate of heat supplied to the binary cycle is a sum of rates of heat supplied in the boiler to the upper cascade and the waste heat exchanger to the lower cascade:

$$\dot{Q}_d^B = \dot{Q}_d^G + \dot{Q}_d^D = \dot{m}_p^G \left(h_1^G - h_4^G\right) + \dot{m}_n^D \left(h_5^D - h_4^D\right). \tag{16}$$

The rate of removed heat from the binary cycle is equal to the rate of heat removed from the lower cascade:

$$\dot{Q}_w^B = \dot{Q}_w^D = \dot{m}_n^D \left(h_{2s}^D - h_3^D\right). \tag{17}$$

The power of a binary cycle is equal to the sum of powers of a lower and a higher cascades:

$$N_{C-R}^B = N_{C-R}^G + N_{C-R}^D \, . \tag{18}$$

The efficiency of a binary cycle is described by a relation:

$$\eta_{C-R}^B = \frac{N_{C-R}^B}{\dot{Q}_d^B} = \frac{N_{C-R}^G + N_{C-R}^D}{\dot{Q}_d^G + \dot{Q}_d^D} \, . \tag{19}$$

THE RESULTS OF CALCULATIONS AND THEIR ANALYSIS

The results of calculations of particular design of power plants have been tabulated and presented in a form of charts which then served as a foundation for comparative analysis and formulation of final conclusions. Selected sample results of calculation for both cases of power plants have been presented graphically in subsequent figures (Fig. 5–9).

In figure 5 presented has been the relation between the power of a binary power plant and a superheating temperature and pressure, obtained for a selected sample working fluid used in a lower cascade (R227ea), for a specified condensation/evaporation temperature of 98/55 ^{o}C.

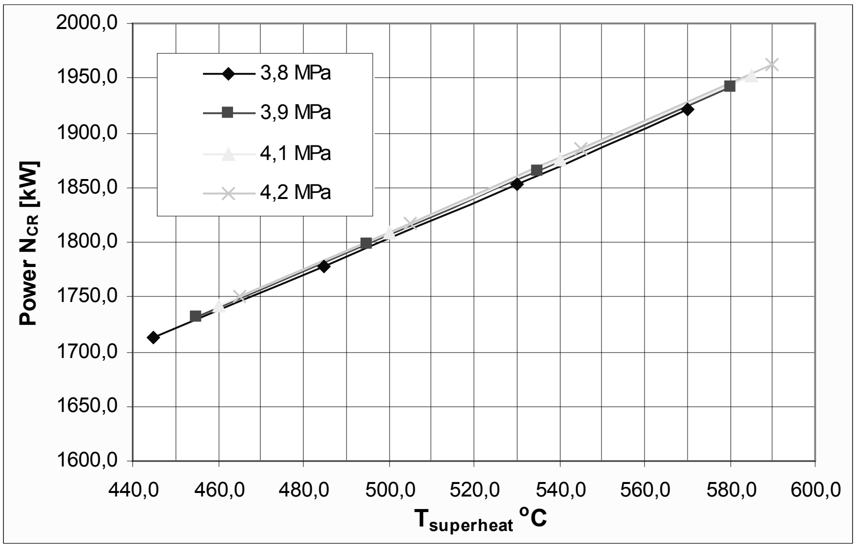

Fig. 5. Relation of binary plant power on superheating temperature and pressure, for a condensation/evaporation temperature of 98/95 ^{o}C

In Fig. 6 presented has been the relation between the power of a binary power plant and superheating temperature and pressure, obtained for a selected sample working fluid used in a lower cascade (R227ea), for two remote values of condensation/evaporation temperatures (98/55 ^{o}C and 58/55 ^{o}C).

In Fig. 7 compared has been the power of binary power plant and a reference power plant determined in function of superheating temperature and pressure, obtained for a selected sample working fluid used in a lower cascade (R227ea), for two extreme values of condensation/evaporation temperatures.

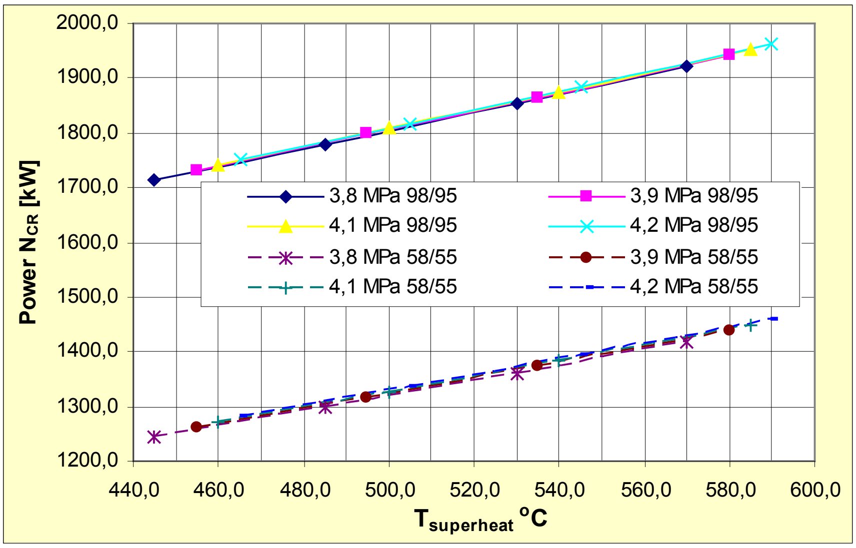

Fig. 6. Relation between the power of binary power plant and superheating temperature and pressure, for condensation/evaporation temperatures of 98/95 °C and 58/55 °C

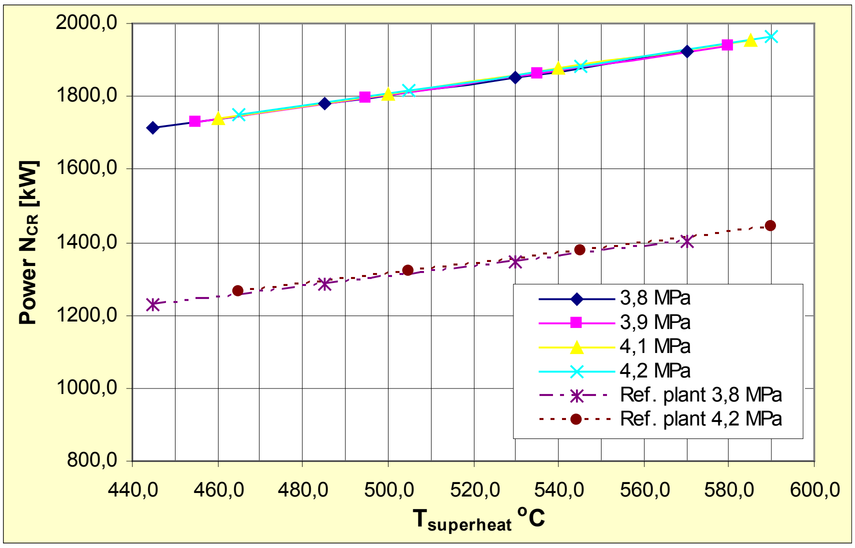

Fig. 7. Relation between the power of binary plant and superheating temperature and pressure, for condensation/evaporation temperatures of 98/95°C and a given power of a reference plant for the pressure of 3,8 and 4,2 MPa

In Fig. 8 presented has been the increase of a power of binary power plant with respect to a reference power plant, determined for the same superheating temperatures and pressures as well as selected condensation/evaporation temperatures (98/55 °C and 58/55 °C).

In figure 9 presented has been the efficiency of a binary power plant in function of superheating temperature and pressures as well as selected condensation/evaporation temperatures (98/55 °C and 58/55 °C).

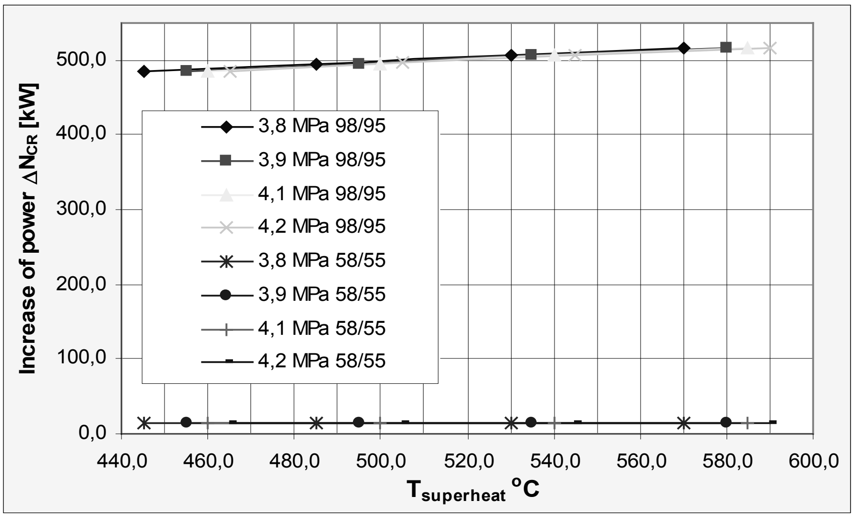

Fig. 8. Increase of power of binary power plant with respect to the reference plant in function of condensation/evaporation temperatures of 98/95°C and 58/55 °C

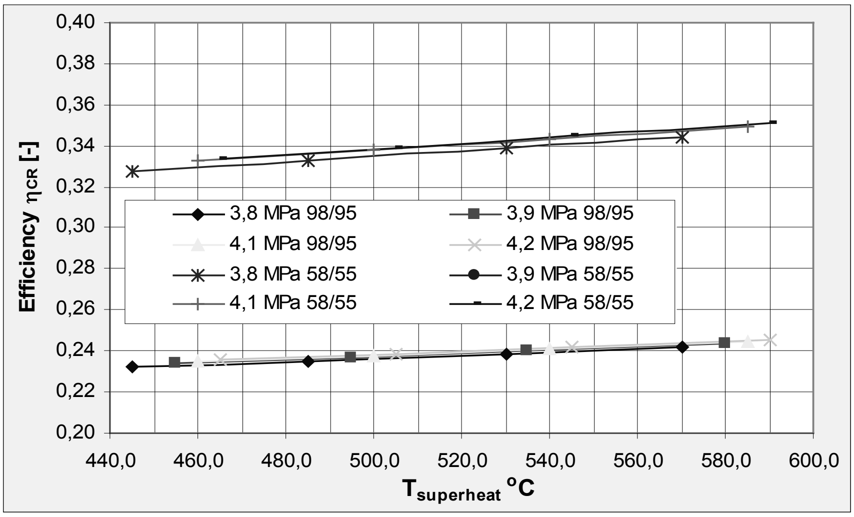

Fig. 9. Efficiency of binary plant in function of superheating temperature and pressure for different values of condensation/evaporation temperatures of: 98/95 and 58/55 °C

ANALYSIS OF THE RESULTS OF CALCULATIONS

In the paper, using the calculation model of a binary power plant, with water and organic substance as working fluids, supplied with energy from combustion of fossil fuels and co-supplied with waste energy of low-temperature heat carrier, accomplished have been calculations of power and efficiency of analysed power plant. Obtained results have been compared with values of power and efficiency obtained for a conventional power plant with water as a working fluid.

The results of analysis relate to thermal parameters of superheated steam supplied to the turbine of a reference power plant as well as a turbine of the upper cascade of binary power plant in the range $T_1 = 411 - 434$ °C, $P_1 = 3{,}9 - 4{,}2$ MPa, for temperatures of condensation/evaporation being respectively 48/45; 58/55; 68/65; 78/75; 88/85 and 98/95 °C. The mass flow rate of steam has been assumed as $\dot{m}_p = 1\,\mathrm{kg/s}$. The condensation temperature in the reference power plant, as well as in the lower cascade of the binary plant is the same and is equal to 29 °C.

In the comparative assessment of the effectiveness of operation of binary plant two indicators have been employed, namely:

- the increase of binary plant power with respect to the reference plant.
- efficiency of binary and conventional plant.

On the basis of presented and analysed results of research it has been concluded that application of the organic fluid in a lower cascade of a binary plant enables to increase the share of low-temperature waste energy. On the other hand, in order to assess the influence the parameters of steam supplied to turbine in the upper cascade on the effectiveness of operation of binary plant the investigations have been carried out for different thermal parameters of steam in the upper cascade, at the assumption that following conditions are fulfilled:

- vapour of organic fluid supplied to turbine is a saturated steam,
- turbine in the upper cascade is supplied with steam featuring such parameters that the end of its isentropic expansion is in the wet steam region, as close to the saturation line $x = 1$ as possible.

On the basis of obtained results there has not been concluded an important influence of thermal parameters of steam in the upper cascade on the increase of power of binary power plant. On the other hand thermal parameters of steam in the upper cycle have a significant influence on the value of efficiency of binary plant. In the case of the same specific entropy of steam at inlet to the turbine the changes of temperature and pressure of steam have no influence on the power of binary plant.

FINAL CONCLUSIONS

On the basis of analysis of results of investigations the following final conclusions can be formulated:

- The extent of increase of binary plant power is firstly influenced by temperatures of condensation and evaporation in the condenser-evaporator heat exchanger type as well as a kind of used organic fluid in the lower cascade of binary plant ; the increase of these temperatures influences positively the increase of power of binary plant.
- if the specific entropy of steam at inlet to the turbine of the upper cascade is the same then the thermal parameters of steam at inlet to the turbine of upper cascade have no influence on the increase of power of binary plant.
- If the final state of expansion is found in the superheated steam region at prescribed thermal parameters of superheated steam at inlet to the turbine of upper cascade, then the reduction of superheating temperature or increase of evaporation pressure renders the reduction of power increase of binary plant. On the other hand increase of superheating temperature or reduction of pressure renders increase of power increase of binary plant. It ought to be noticed, however, that the above mentioned changes of power of binary plant are rather small.
- In all considered cases the thermal parameters of steam, namely temperature and pressure have a significant influence on the extent of efficiency of binary plant.

Acknowledgments

The work has been accomplished in the frame of a research project N N513 419334 funded by the Ministry for Science and Higher Education.

References

1. Badr O., Probert S.D., O’Callaghan W.P. Selecting a working fluid for a Rankine-cycle engine. *Applied Energy,* 1985. Vol. 21. Pp. 1–42.
2. Hung T.C., Shai T.Y., Wang S.K.: A review of Organic Rankine Cycles (ORCs) for the recovery of low-grade waste heat // *Energy* 1997; 22 (7). Pp. 661–667.
3. Chmielniak T.: Energy conversion technologies, Silesian University of Technology Publishers, Gliwice, 2004 (in Polish).
4. Laudyn D., Pawlik M., Strzelczyk F.: Power plants, *WNT*, Warsaw, 1997 (in Polish).
5. Assessment of the influence of thermal parameters of superheated steam at turbine inlet of the upper cascade on the effectiveness of operation of binary power plant. Unpublished report of heat Technology Department of Szczecin University of Technology, Szczecin, 2007 (in Polish).