COMPARISON OF ENERGY INDEXES OF STEAM AND BINARY GEOTHERMAL POWER PLANTS

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KEYWORDS

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ABSTRACT

A generalized principal scheme of a geothermal power plant (GeoPP) is considered. The scheme gives the possibility to analyze various variants of the geothermal fluid utilization: production of electricity by means of a steam turbine fed by the steam separated from the geothermal fluid; utilization of the geothermal fluid to heat up a low boiling working media and expanding it in a turbine to produce electricity; producing power using both turbines.
The elaborated mathematical model makes it possible to calculate the main energy indexes of the schemes using the geothermal fluid parameters (temperature, steam quality, flow rate) and the ambient temperature, which determines the lower temperature of the thermodynamic cycle. As variables in the analysis the following values are used: back pressure at the steam turbine exit, type of low boiling working media, flow rate and maximum pressure in the low boiling loop. Two versions of heat supply to the low boiling loop are considered: only heat of the separated from the geothermal fluid steam and both this steam and also of the separated water. In the last case a limitation is introduced – the geothermal water should not be cooled down less than a prescribed temperature to avoid scaling of the superheater.
The numerical simulation of the GeoPP was carried out using the TRNSYS software.
The following low boiling substances were analyzed: fluorocarbons R12 and R134a, as well as propane, butane, isobutene, pentane, isopentane and ammonia. Appropriate equations of state for these substances were used.
The analysis was carried out for the power unit for the Verkhne-Mutnovskaya GeoPP, which is now in the design stage: temperature of the geothermal fluid 162°C, steam quality 0.3 and flow rate 36.6 kg/s. Ultimate values of the geothermal unit power were determined for various considered schemes.
A simplified analysis of GeoPP parameters sensitivity to changes of initial parameters was carried out. In particular the influence of the steam quality is analyzed.
The work was done in close cooperation with the companies «Geotherm» and «Nauka» – leading enterprises in the field of GeoPP implementation in Russia and was financially supported by the Russian Basic Research Foundation (grant 03-02-16637).

1. INTRODUCTION

Nowadays in Russia one can observe a certain progress in geothermal energy usage, which is conditioned by the necessity to solve the acute energy supply problems for the remote regions. Those regions sometime have large proved reserves of high temperature geothermal fluids. At the same time the domestic industry has significant achievements in producing advanced equipment for GeoPP [1]. Commissioning in Kamchatka in 1999 a pilot GeoPP Verchne-Mutnovskaya with capacity 12 (3x4) MW and in 2002 of the first stage of the Mutnovskaya GeoPP with capacity 50 (2x25) MW has disclosed new perspectives, technical and financial options for development of efficient technologies for utilization of geothermal resources also in other Russia' regions

One of perspective options to enhance utilization of geothermal heat for electricity production is the usage of binary installations, which operate more efficient at lower geothermal fluid temperatures than it is practiced with steam turbines.

In this paper we are considering a generalized principal combined scheme of a GeoPP, which include the following options of geothermal fluid heat utilization:

- production of electricity by means of a steam turbine, which uses steam separated from the geothermal fluid;
- utilization of the geothermal fluid heat to heat up a low boiling substance and expand its vapor in a turbine;
- combined production of electricity using both turbine types.

A mathematical model of the GeoPP is elaborated to calculate the main scheme parameters as function of the following data:

- temperature, steam quality and flow rate of the geothermal fluid at the entrance of the GeoPP;
- ambient air temperature, which determines the lower cycle temperature;
- back-pressure at the steam turbine exit.

Theoretically there is a limiting case when this back-pressure becomes equal to the pressure in the geothermal well mouth; in this case the electricity is produced only by the low boiling turbine. Another limiting case is obtained when the back-pressure at the steam turbine exit is equal to the saturation pressure at ambient air temperature; in this case power is produced only by the steam turbine except the option to use the separated water to heat up the low boiling working media. In between the power is produced simultaneously by both turbines;

- low boiling working media type. The following low boiling substances were analyzed: fluorocarbons R12 and R134a, as well as propane, butane, isobutene, pentane, isopentane and ammonia. Appropriate equations of state were used for these substances;
- flow rate and maximum pressure of the working media in the low temperature loop. Variation of these data gives the possibility to arrive to a set of parameters, which define the maximum unit power when all other parameters are fixed.

The model supposes usage in the low temperature loop only the heat transferred from the separated steam (a "clean" scheme), as well as also the heat of the separated geothermal water. In this last case the temperature drop of the geothermal water is limited to avoid scaling in the superheater.

The main goal of the mathematical analysis presented in this paper was to determine the maximum power of the geothermal unit, which is now designed for the Verkhne-Mutnovskaya GeoPP. The geothermal well prepared for this unit produces 36.6 kg/s of geothermal fluid having a temperature 162°C, and steam quality 0.3.

2. MODELLING OF THE GeoPP OPERATION

2.1 The generalized scheme of a combined GeoPP

The generalized scheme of a combined GeoPP is presented on Figure 1.

The generalized GeoPP scheme provides for electricity production by both steam turbine III and low boiling substance turbine VII. Using this scheme it is also possible to study limiting cases of GeoPP operation, when only one of those turbines produces power.

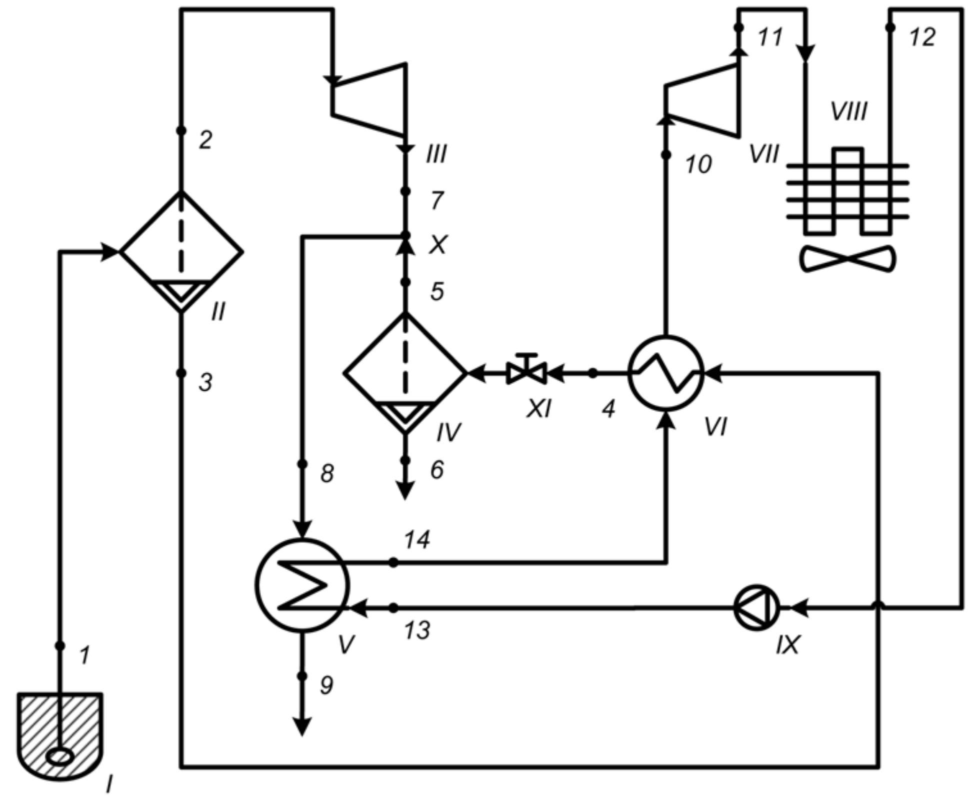

Figure 1. The generalized scheme of a combined GeoPP

I – geothermal well, II, IV –separators, III –steam turbine, V, VI –heat exchangers, VII – turbine using low boiling working media, VIII –air cooled heat exchanger-condenser, IX –pump, X –mixer, XI – throttle

In general the geothermal fluid from the well I is flowing to the separator II, dividing the flow into steam, which is carried over to the steam turbine III. The separated water enters the heat exchanger VI, where it heats up the low boiling working media entering the turbine VII, afterwards is throttled down to the pressure equal to the back-pressure of the steam turbine and finally is carried over to the separator IV. The evolving steam is mixed with steam exiting from the turbine III, and flows to the heat exchanger V – the first stage of low boiling working media heating. The condensate from the heat exchanger V and the geothermal water separated in the separator IV are discharged. The low boiling working media circulates in a closed loop: the vapor is raised in the heat exchangers V и VI and enters the turbine VII, after expanding in the turbine the vapor is condensed in an air cooled condenser; the condensate by means of the circulating pump IX is again pumped to the heat exchanger V.

From the thermodynamic point of view the GeoPP operation is performed in the range of temperatures T_{max}, corresponding to the temperature of the geothermal fluid recovered from the well, and T_{min}, determined by the ambient air temperature, which is used as a heat sink in the air cooled condenser.

The above mentioned limiting cases are realized at the following conditions:

A) If the back-pressure at the steam turbine exit becomes equal to the pressure in the separator II, only the low boiling turbine will produce electricity;

B) If in the steam turbine the steam expands down to the pressure corresponding to the ambient air temperature T_{min}, and the heat of the separated in the separator II geothermal water is not used to heat up the low boiling fluid, then the electricity is produced only by the steam turbine.

In case when the separated geothermal fluid heat is used the scheme allows to limit its cooling down in the heat exchanger VI to avoid scaling of the heat exchanger surface.

2.2. Modeling of the GeoPP scheme and operation modes

GeoPP modeling was carried out using the TRNSYS software [2] including standard or specially elaborated modules of the calculation scheme.
The steam separator is considered in an ideal approximation without heat and other losses. At the separator entrance the pressure, flow rate and steam quality of the geothermal fluid are set, at the exit – quality of the separated steam. Calculated are the steam flow rate to the steam turbine and the flow rate of the separated thermal water.
The turbine stage (steam turbine and low boiling turbine) is modeled by calculating its parameters using the entrance and exit pressures, steam (vapor) flow rate and quality at the stage entrance. Using the preset stage efficiency the vapor temperature and quality at the stage exit are determined, as well as the work performed by the turbine. Provision for calculation of a single or multistage turbine is made including moisture separation between the stages.
The heat exchanger is modeled using a generalized model [3] providing for taking into account phase transition in one or both energy carriers. Using the preset energy carriers temperatures, pressures and flow rates and the efficiency of the heat exchanger [3] the exit temperatures and vapor qualities of the heat carriers as well as the transferred thermal power are calculated.
The steam condenser similar to the separator is modeled in an ideal approximation. Using the preset entrance temperature and vapor quality and the condensation temperature the pressure in the condenser and the rejected heat are calculated.
The steam-steam mixer (X). Preset are temperatures, steam qualities and flow rates of both flows entering the separator as well as the pressure. Calculated are the exit temperature, flow rate and steam quality. Heat losses are neglected.
The throttle (XI) is modeled supposing that the steam expands isoenthalpic from the entrance pressure down to the exit pressure. Preset are the entrance temperature, pressure and steam quality as well as the exit pressure. Calculated are the exit temperature and steam quality.
The thermodynamic properties of the working media were described using the corresponding equations of state. Fluorocarbons R12 and R134a, propane, butane, isobutene, pentane, isopentane and ammonia were considered as low boiling working media. The properties of fluorocarbons and ammonia were calculated using standard modules of the TRNSYS. The properties of hydrocarbons were calculated by means of a generalized van der-Vaals equation of state [4, 5], which is valid in the pressure range up to 100 MPa and temperature up to 200^{o}C.
A typical view of the calculation scheme presenting the information flows connecting the scheme elements in a graphical TRNSYS interface is given on Figure2.
During GeoPP modeling the flow rate, temperature and steam quality are considered as **fixed parameters**. For the Verkhne-Mutnovskaya GeoPP the corresponding parameters are: 36.6 kg/s, 162^{o}C (the corresponding saturation pressure is about 0.65 MPa) and 0.3.
In addition as **fixed** the low-boiling fluid temperature at the exit of the air-cooled condenser was determined. In all calculations it was assumed as 30^{o}C.
Preset was also the temperature of the geothermal water at the exit of the heat exchanger VI. The reason was to avoid possible heat exchanger surface scaling taking into account the geothermal fluid chemical composition. The choice of the admissible cooling down of the thermal water is a separate problem. In our calculations the lowest temperature was taken as 145^{o}C.
As **variables** in the problem the following parameters were considered: back-pressure at the steam turbine exit, which was altered in the range determined by the maximum and minimum cycle temperatures T_{max} and T_{min}; pressure and flow rate of the low-boiling working media at the turbine entrance. For each back-pressure the optimum combination of the pressure and flow rate of the low-boiling working media was determined, which gives the maximum power output of the low-boiling turbine and hence maximum total power of the GeoPP.

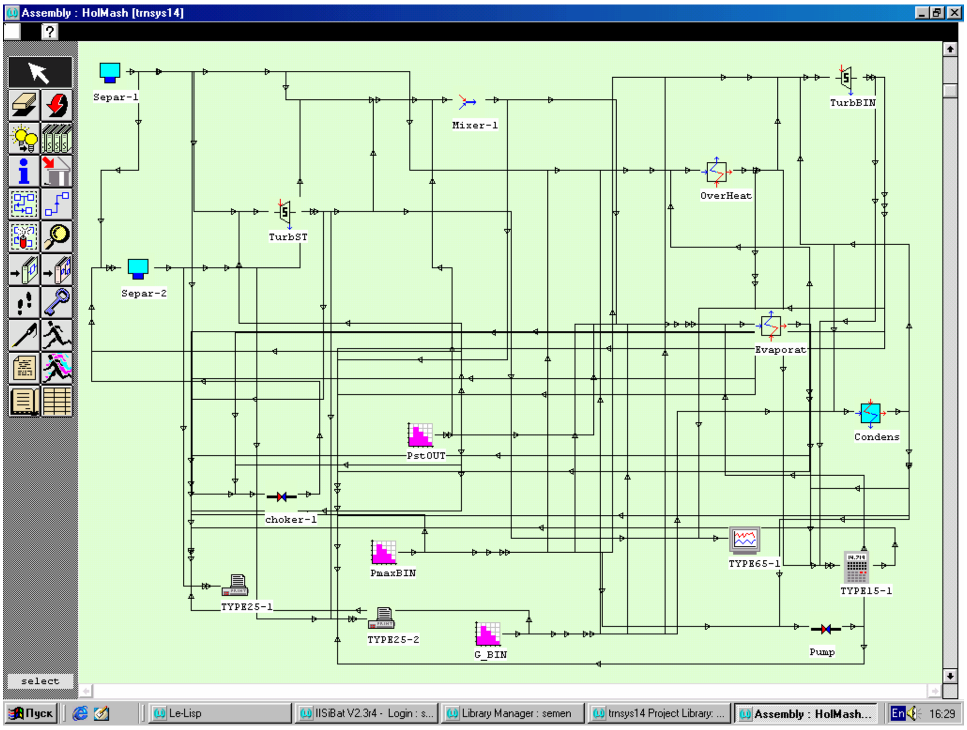

Fig. 2. Screenshot of the GeoPP calculation scheme under TRNSYS 14.2

In this analysis the parasitics of the GeoPP (energy expenses for circulating pumps operation and other plant needs) were neglected.

During the modeling procedure the humidity content of the steam (vapor) at the corresponding turbine stage exit was checked. Variants were the humidity exceeded 15% were omitted. At this stage of analysis the low-boiling turbine in all cases operate at pressures lower than critical.

3. CALCULATION RESULTS

The main results of the combined GeoPP power calculations adopted to the operation conditions of the Verkhne-Mutnovskaya plant are summarized at the Figure 3. Here the steam turbine and total plant power are plotted against the back-pressure at the steam turbine exit.

As the back-pressure increases the steam turbine power drops and when the pressure reaches 0.65 MPa, equal to the pressure of the geothermal fluid at the well mouth, it approaches 0.

The set of curves at the upper part of the figure gives the total GeoPP power for various low-boiling working media. The low-boiling turbine power is the residual of the total and steam turbine power. Along with back-pressure increase the low-boiling turbine power increases approaching its maximum at the limiting case, when electricity is produced only by the low-boiling turbine.

The curve representing the total power of the unit for most of considered working media has an acclivous maximum for the back-pressure around 0.1 MPa.

The obtained results of comparison of various working media are not enough to arrive to a definite conclusion about their thermodynamic advantages, because the discrepancy between the data does not exceed 10-15% from the unit power. Having this in mind the main criterion for the choice of one or another working media should be their operation characteristics, safety considerations and cost.

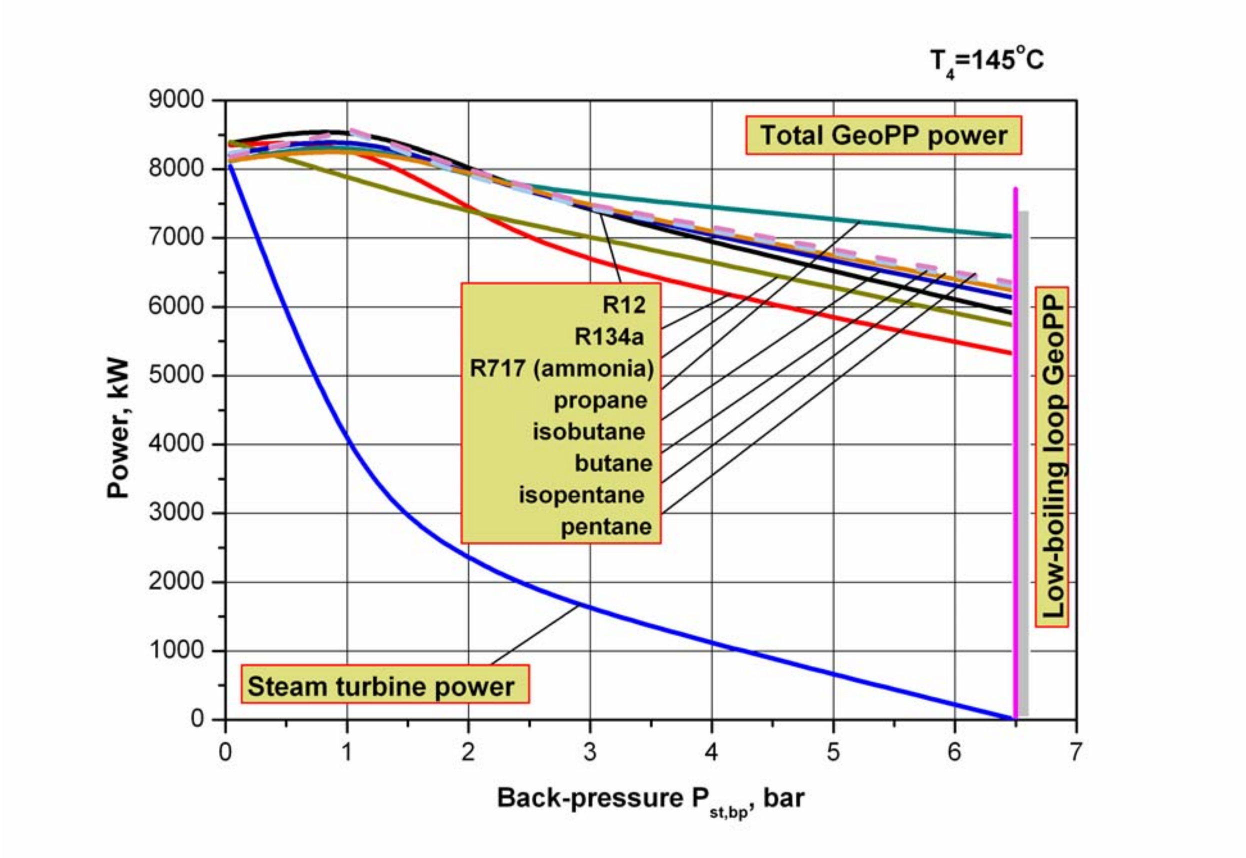

Figure 3. Results of a combined GeoPP power calculation as a function of the steam turbine back-pressure

To arrive to a final decision concerning the design of the GeoPP unit with a low-boiling turbine it is expedient to consider two principal scheme options:

- a combined scheme with both steam and low-boiling turbines at a back-pressure at the steam turbine exit about 0.1 MPa. Along with providing a maximum total power (about 8.5 MW) such scheme as compared with a conventional steam turbine GeoPP makes it possible to exclude vacuum equipment needed for extraction of gases dissolved in the geothermal fluid, as well as a vacuum steam condenser;
- a scheme using only the low-boiling working media turbine. In this scheme the total heat potential of the geothermal fluid is used in the low-boiling loop. With the geothermal fluid parameters for the defined geothermal field (G=36.6 kg/s, t=162^{o}C, x=0,3) this scheme can guarantee production of 5.5 – 7 MW of power depending on the chosen working substance. It should be emphasized that in spite of less power this scheme may be preferable because it does not need the steam turbine. The separators II and IV become also unnecessary substantially decreasing the unit' cost.

It is also important to mention that the efficiency of the plant using only the low-boiling turbine and the unit power can be substantially increased by some improvements of the considered generalized scheme. The above presented results appertain to the limiting operation case of the GeoPP, namely when the back-pressure at the steam turbine exit is equal to the geothermal fluid pressure at the well mouth and the cooling down of the geothermal water is limited (not less than 145^{o}C) to avoid scaling. It means that the scheme suffers from substantial limitations. However the useful heat potential of the geothermal fluid can be increased if from the scheme presented on Figure 1 to exclude the separator II and the steam turbine, and the total geothermal fluid introduce directly into the heat exchanger VI, the separator IV use to obtain clean steam at pressure about 0.1 MPa and submit to the cycle additionally its condensation heat in the heat exchanger V. This approach also practically excludes the scaling risk. Preliminary calculations of the performance of this improved scheme of the GeoPP using only the low-boiling turbine demonstrate that its power can be increased up to 8 – 8.5 MW.

4. SENSITIVITY OF CALCULATED INDEXES OF THE GeoPP TO CHANGES OF THE PRESET PARAMETERS

The above presented calculation results are obtained for concrete fixed parameters of the geothermal fluid (G=36.6 kg/s, t=162^{o}C, x=0,3) and fixed lower cycle temperature (30^{o}C). However these parameters can vary substantially for various geothermal fields and climatic conditions at the plant site.

First, when in a binary GeoPP an air-cooled condenser is used the ultimate cooling down of the working media substantially depends on the ambient air temperature and can significantly vary depending on the time of the day and the year season.

From the other side various geothermal fields have different fluid temperatures and steam quality. During the operation time of a geothermal well its parameters can also be altered.

Having this in mind, it is interesting to analyze the sensitivity of the obtained results of the GeoPP power from altering of some key parameters. Detailed analysis of operation of the GeoPP equipment at parameters differing from rated is a separate and rather complicated problem. Below we make an attempt to give a simplified analysis.

From general thermodynamic considerations the power N produced by the installation, taking into account the Carnot cycle efficiency can be expressed as

$$N = \eta \frac{T_{\max} - T_{\min}}{T_{\max}} Q , \qquad (1)$$

were Q – is the available thermal power of the geothermal well, T_{max} and T_{min} – correspondingly the upper and lower cycle temperatures in the GeoPP, η – the inner installation efficiency depending on the working media properties, which define the difference between the real cycle and the Carnot cycle, and on operation efficiency of the installation equipment components (for the above considered scheme options η is about 45-50%).

Assuming that in the considered below alteration range of the regime parameters the inner installation efficiency is constant (as a matter of fact this efficiency as a rule decreases, when the parameters differ from the rated), it is possible using the equation (1) evaluate the influence of the maximum and minimum cycle temperatures on the installation power. The results are presented on Figure 4.

It shows that when T_{min} differs by 10^{o}C from the fixed in previous calculations value T_{min}=30^{o}C the relative alteration of the produced power *N/N**, where *N** -is the power of the unit consisting only of a low-boiling turbine using isobutane as a working media in the rated regime (G=36.6 kg/s, T_{max}=162^{o}C, x=0,3, T_{min}=30^{o}C), is equal to about 10%. The alteration of T_{max} by the same 10^{o}C from 162^{o}C changes the *N/N** ratio also by about 10%.

These assessments results are rather approximate and are only exemplary. However they emphasize the importance of the problem of changing regime parameters on the operation of a concrete installation as well as on the selection of the equipment when a new geothermal field is considered. It is obvious that this problem deserves a special study.

On Figure 5 the influence of the steam quality on the GeoPP power is presented for 3 cases of the above described scheme: GeoPP with only a steam turbine, a combined GeoPP with back-pressure at the steam turbine exit 0.1 MPa and a GeoPP only with a low-boiling turbine using isobutene. The calculations were made assuming that the temperature and flow rate of the geothermal fluid remain the same as for the Verkhne-Mutnovskaya GeoPP, the lower cycle temperature t_{min} = 30^{o}C was also not altered. Only the steam quality was varied.

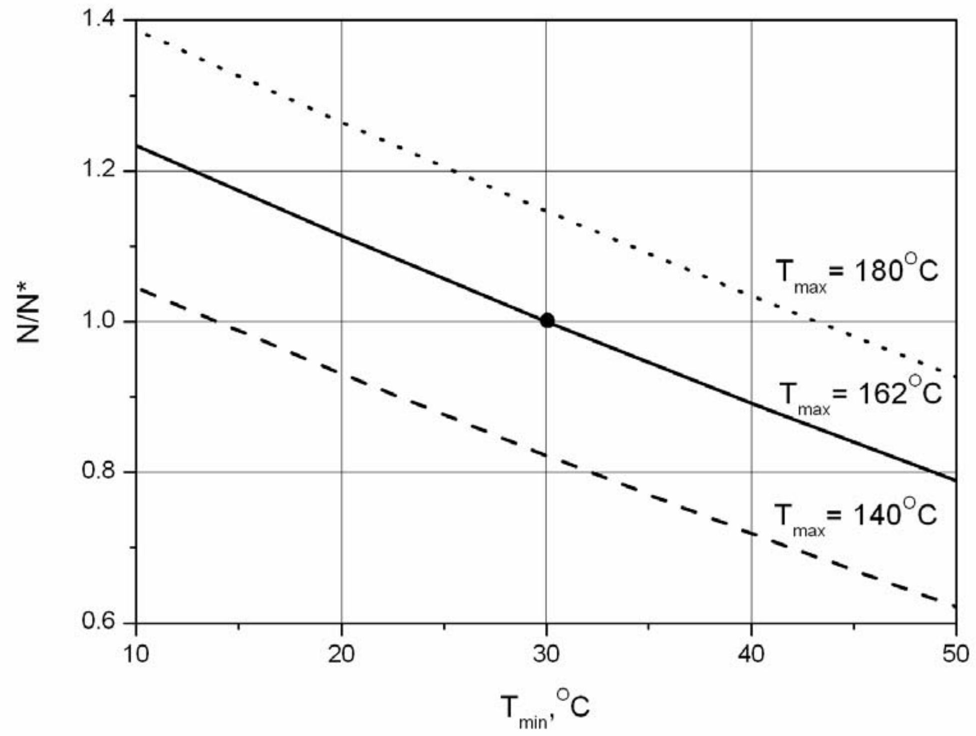

Figure.4. Influence of upper and lower cycle temperatures alteration upon the GeoPP power

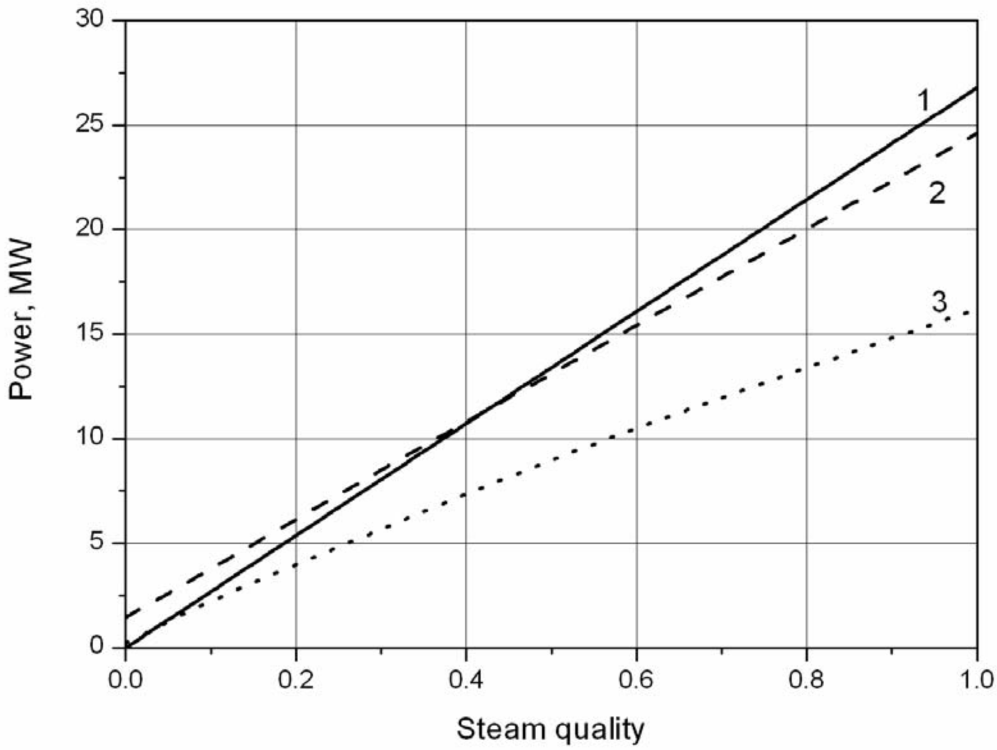

Fig. .5. Influence of initial steam quality on the GeoPP power

1 –GeoPP only with a steam turbine, 2 –a combined GeoPP having a back-pressure at the steam turbine exit 0.1 MPa, 3 – GeoPP only with a turbine operating on isobutene

It can be seen that the initial steam quality strongly influence the GeoPP power. For instance for the above analyzed unit for the Verkhne-Mutnovskaya GeoPP decrease of steam quality from 0.3 to 0.2 decreases the calculated unit power by 30–40%.
The strong dependence of the GeoPP energy indexes from the initial geothermal fluid steam quality calls for rather accurate definition of the initial parameters for the plant design, as well for necessity to analyze the influence of steam quality alteration during life time of the equipment upon the plant output.

5. CONCLUSIONS

Mathematical models and relevant software for theoretical analysis of GeoPP performance were developed including schemes using various low-boiling working media. Using a generalized principal scheme an energy analysis of the designed binary Verkhne-Mutnovskaya GeoPP was performed. The power of the unit was estimated for various scheme options. A simplified approach to assess the sensitivity of the GeoPP energy indexes on the alteration of main regime parameters was developed. Necessity of more detailed study of this problem was indicated.
The elaborated approaches and the software can be used for design of GeoPPs taking into account real equipment characteristics and adopted plant schemes.

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