REPORT

Advanced efficient cycles and schemes for geothermal energy conversion in the frame of FP6 project “ENGINE”

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Summary

1. Introduction

Taking into account the recent tendency of significant growth of traditional energy sources prices, forecasts concerning their scarcity and environmental issues of their usage in many countries R,D&D projects are initiated aimed at enhancing the role and input of the renewable energy sources in the energy supply pattern. Among them is also the geothermal energy. It is a kind of energy, which appears as physical heat of fluids existing in the earth entrails at different depth as well as the physical heat of hot dry rocks. The most important characteristic of the geothermal energy is the temperature. Usually it is considered that to use the geothermal energy for power production its temperature potential should be not less than 100^{o}C. Unfortunately there are not much geothermal fields with fluids having such high temperature. Therefore the attention is drawn to Enhanced Geothermal Systems, which is the essence of the “ENGINE” project. In particular the problem is to increase the geothermal resource base providing access to the enormous potential of heat accumulated in dry rocks.

The second problem is to decrease the cost of electricity produced by a geothermal power plant (GeoPP). It is well known that the main input in the geothermal electricity cost gives the capital cost of the underground part of the GeoPP, the deep well drilling and in the case of hot dry rocks using creating the necessary fracture structure and maintaining its uniform permeability. The cost of electricity depends also on the amount of energy which can be produced per unity of flow rate of the recovered geothermal fluid, or per unity of water flow rate pumped through the underground circulating system. The last issue supposes optimization of the GeoPP scheme and the thermodynamic conversion cycle. The report is mainly devoted to solve this optimization problem.

Russia is one of the countries which have significant geothermal resources. According to estimates up to 10% of the current country energy needs and for some regions (North Caucasus, Kamchatka, Kurila islands) – up to 50-90% can be covered by geothermal energy.
The primary tasks to enhance geothermal energy utilization in Russia are:

– specification of the geothermal resources potential in the country as a whole and in some most promising regions;

–perfection of geothermal energy recovery technologies including advanced equipment.

In the frame of the above mentioned tasks it is necessary to perform a system analysis of existing schemes and cycles for conversion of geothermal energy into electricity and heat as well as development of new efficient cycles and schemes of GeoPP. Thus these activities coincide with the goal of the “ENGINE” project.

The recently existing geothermal power plants predominantly use as a primary energy source underground geothermal fields where the fluids are pressurized steam-water mixtures with various quality. This two-phase flow is recovered to the surface, the steam is separated and expanded in a steam turbine. Sometime additional amount of steam is produced by flash evaporation of the remaining water and fed to low pressure sections of the steam turbine. The steam turbine of a GeoPP usually operates in conditions, which are quite different from those for modern power plants. The main difference constitute the inlet steam parameters. For a GeoPP it is saturated steam with modest temperature, whereas for a conventional power plant it is superheated steam with high temperature and pressure. During expansion of saturated steam the working fluid becomes the more humid the less is the ultimate expansion pressure and the higher is the initial steam temperature. To avoid erosion of turbine blades the steam humidity should not exceed some 10 %.Therefore for a GeoPP there are two options: to expand the steam only down to the atmospheric pressure (about 0,1 MPa), in this case the humidity will be limited and a more simple condenser may be used; to expand the steam down to the ambient temperature (the corresponding back pressure is some 4 kPa), in this case more power will be produced, however the turbine should be designed to separate the excess moisture and a more sophisticated vacuum condenser should be used.

The heat content of the separated and flash evaporated water can be used as a low potential heat source for different applications including power production. In the last case the heat from the separated water should be transferred to a low boiling working fluid, which circulates in a closed loop Rankine cycle. To produce maximum power it is expedient to cool the water down to as low temperature as possible. The limit usually is defined by precipitation of some substances dissolved in the water. As far as the geothermal water contains some hazardous components before precipitation it should be reinjected underground sometime to the same strata. Usually it is considered that a GeoPP using such a simple scheme can be economical if the initial temperature of the geothermal fluid is not less than some 100^{o}C.

Since the ENGINE project is devoted to enhanced geothermal systems in this study the authors have tried to develop and analyze a generalized scheme of a GeoPP, where the power is produced both by a steam turbine from the separated and flash evaporated steam and in a low temperature Rankin cycle running by a some low boiling working fluid using as a heat source the remaining heat of the used geothermal fluid. This approach includes also two limiting cases: when the total power of the GeoPP is produced by the steam turbine, and when there is no steam turbine and the total power is produced by the low boiling turbine.

The goal of the study is to develop a mathematical model of such generalized scheme for geothermal energy conversion. Using this model it became possible to suggest schemes and low boiling working fluids providing for maximum thermodynamic efficiency of a GeoPP and apply the results to a case study of a planned GeoPP at the Pauzetka geothermal field (Kamchatka).

A section of the report is concerned with GeoPP based on heat extracted from hot dry rocks. In this case it is assumed that an underground circulating system will be created. Thus the primary energy source would be a water flow with a given flow rate, temperature and pressure. An analysis was carried out to determine the maximum specific power which can be produced by 1 kg/s flow of water with a given temperature. The advantages of supercritical Rankin cycles were demonstrated and the role of temperature pinch in the counter-flow heat exchanger with low boiling working fluid elaborated.

2. Russian experience in geothermal energy utilization

Geothermal energy utilization in the USSR started in the mid 60ties of the 20th century. In 1964 a North Caucasus expedition for drilling and reconstruction of oil wells for geothermal fluids recovery was organized. As a follow up recovery organizations were established in the North Caucasus and in Kamchatka. During the years 1970 – 1990 the output of geothermal waters increased by a factor of 9 and geothermal steam – by a factor 3,2. In the year 1990 53 mln t of geothermal water and 413 thous t of steam were extracted.

Recently in Russia are explored 47 geothermal fields (more than 3000 wells are drilled) with a capacity about 0,24 mln t/day of thermal water and 0,1 mln m^3/day of steam. The Russia' geothermal industry is mainly concentrated in North Caucasus (Dagestan and Krasnodar Territory, where yearly 8-10 mln t of thermal water with temperatures 50-110°C are recovered) and in Kamchatka, where geothermal steam is recovered. At the Kamchatka geothermal fields 365 wells with depth in the range from 200 to 2500 m are drilled. The proved reserves of these fields can cover the total electricity and heat demand lpllfor Kamchatka during more than 100 years. Along with the Mutnovskoe high temperature geothermal field, which can бgeothermal heat. The total heat resources of Kamchatka are estimated as 5000 MW (th). Rather large geothermal heat resources are located in Chukotka close to the Kamchatka border.

The Kurila islands are also rich with geothermal resources enough to cover their total electricity and heat demand during 100 -200 years. Substantial geothermal resources are located in the Kaliningrad region, where exist hot water reserves with temperature 110°C with an estimated potential of 1000 MW (th).

In the year 2002 started operation two units (25 MW each) at the Mutnovskaya GeoPP. In the late 2007 in the frame of the Federal program "Social and Economic development, of the Kurila islands" at the island Iturup started operation the 3,6 MW(el) "Okeanskaya" GeoPP. At the Kunashir island is operating the GeoPP "Mendelevskaya" : 3,6 MW(el) and 17 Gcal/h (th).

One can conclude that Russia has enough experience and potential to start a more active policy in the field of using non-conventional geothermal resources for power production and thermal applications.

3. Generalized GeoPP scheme

There exist two different approaches to use geothermal fluids for power production. In the first one the power is produced by a steam turbine, which is fed with steam derived by one or another way from the geothermal fluid. The corresponding schemes for this approach are presented on fig.1.

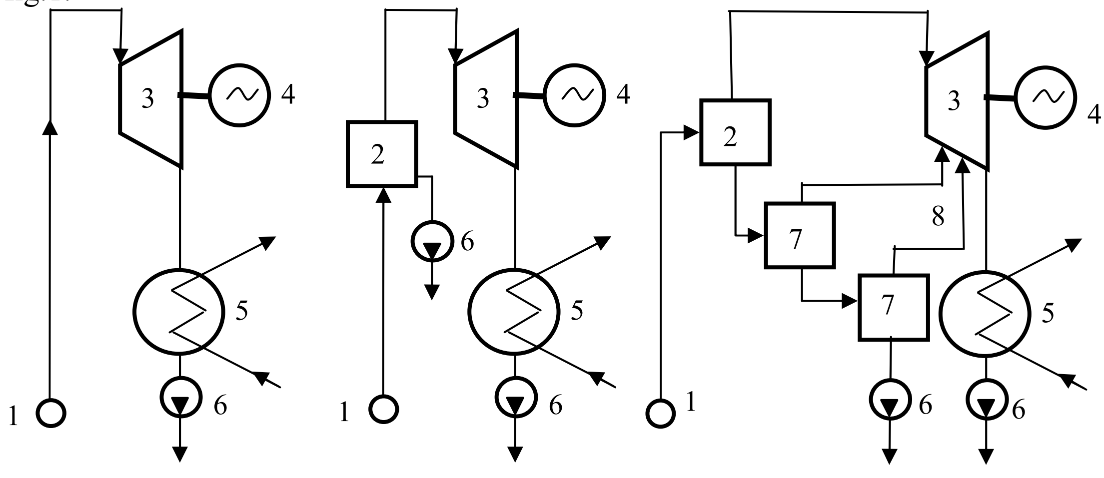

Fig.1. Schemes of GeoPP with power produced by a steam turbine

a) dry saturated steam is directly extracted from the geothermal well;

b) the recovered geothermal fluid is a two-phase system and the steam is separated from the liquid;

c) the geothermal fluid is a two-phase system and the steam is produced in a separator and in a sequence of flash evaporators.

1-production well; 2- separator ; 3- steam turbine; 4- generator; 5- condenser; 6- reinjection pump; 7- flash evaporator; 8- low pressure steam inlet.

In the second approach the power is produced by a turbine using a low boiling liquid vapor produced in a heat exchanger from the geothermal fluid (Fig.2.).

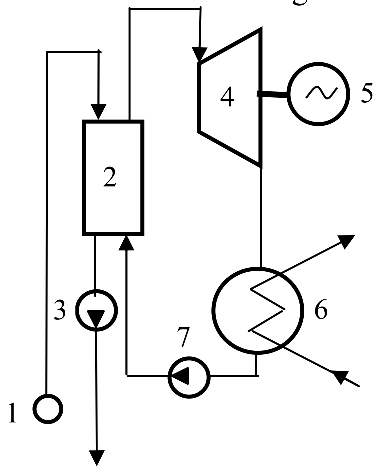

Fig.2. Scheme of GeoPP with power produced by a low boiling vapor turbine

1-geothermal production well; 2 – heat exchanger; 3- reinjection pump; 4- low boiling turbine; 5- generator; 6- condenser; 7- low boiling liquid circulating pump

These both approaches are usually treated separately. However in some cases it is expedient to consider a combined scheme, where the power is produced by both working media. Fig.3. represents such a generalized scheme.

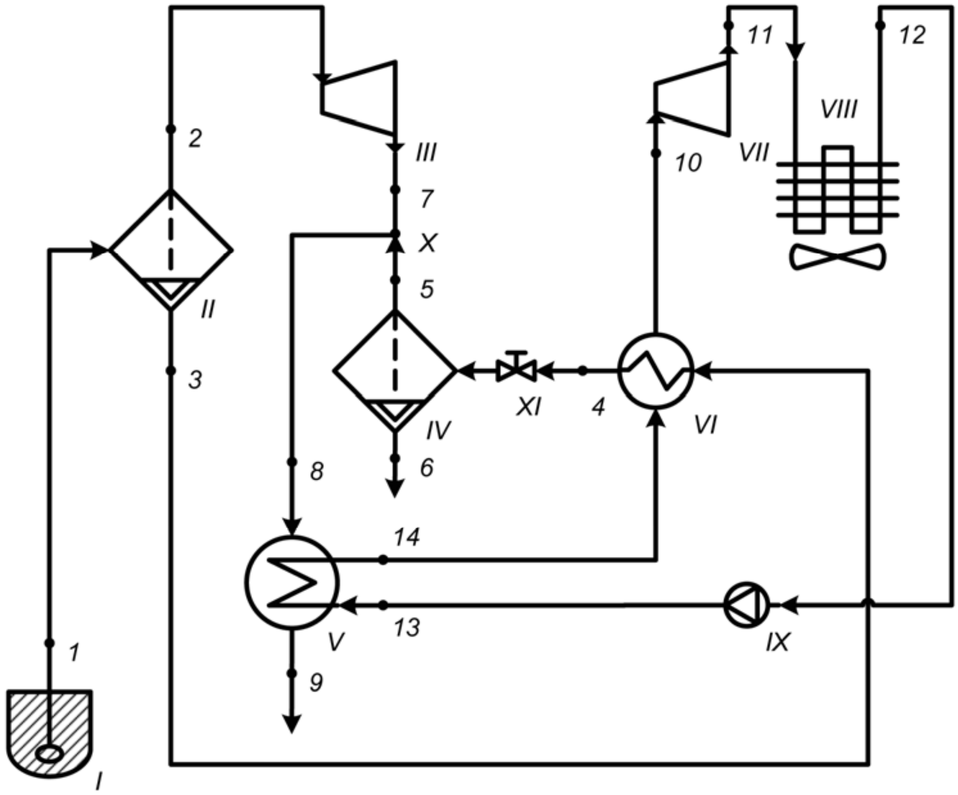

Fig.3. Generalized scheme of GeoPP with power produced by a steam turbine and a low boiling vapor turbine

I – geothermal well; II, IV – separators; III – steam turbine; V, VI – heat exchangers; VII – low boiling turbine; VIII – air cooled condenser IX – pump; X – mixing point; XI – throttle.

1- geothermal well; 2 – separated steam to the steam turbine; 3 – separated water to the low boiling loop; 4 – water flow after the low boiling liquid evaporator; 5 – steam to the mixing unit; 6 – geothermal water to reinjection; 7 – exhaust flow from the steam turbine; 8 – mixed flow to the condenser-heat exchanger; 9 – fresh distilled water; 10 –

vapor flow to the low boiling turbine; 11 – low boiling turbine exhaust; 12, 13 - low boiling liquid flow to the condenser- heat exchanger; 14 – low boiling liquid flow to the evaporator.

In the generalized scheme power is produced by two thermodynamic cycles; the top cycle operates with the geothermal fluid, whereas the bottom cycle with a low boiling liquid. Two flows transfer the heat from the top to the bottom cycle. One is the high temperature and pressure geothermal liquid separated in the separator II. This flow is used to evaporate and sometime superheat the low boiling working fluid in the evaporator heat exchanger VI. The other is the exhaust flow from the steam turbine, which is used to preheat the low boiling liquid in the heat exchanger V. The geothermal liquid temperature after the evaporator VI is high enough, at any rate not less than the boiling temperature of the low boiling liquid at the chosen pressure. The pressure of this flow is reduced in the throttle XI to equalize it with the steam turbine exhaust pressure. By throttling some steam is produced, which is mixed with the steam turbine exhaust and used in the heat exchanger V. The remaining water is reinjected.

The mathematical model of the generalized scheme uses a number of input data:

- pressure, temperature and quality of the recovered geothermal fluid at the well mouth;
- lowest geothermal liquid temperature to avoid precipitation of dissolved components;
- kind of low boiling substance and its thermodynamic properties.

Using the model one can optimize the scheme providing for maximum thermodynamic efficiency, i.e. define the maximum power which can be produced per 1 kg/s of recovered geothermal fluid.

The following variables are considered as free leading to maximum scheme efficiency:

- pressure (and the corresponding temperature) at the steam turbine exhaust;
- low temperature working fluid boiling pressure (and the corresponding temperature);
- temperature of superheated low boiling vapor;
- low temperature working fluid flow rate per 1kg/s of geothermal fluid flow rate.

The generalized scheme advantage is that by varying the pressure (and the corresponding temperature) at the steam turbine exhaust one can obtain the two limiting cases corresponding to schemes Fig. 1 and Fig. 2. In particular if the pressure (and the corresponding temperature) at the steam turbine exhaust are defined equal to the geothermal fluid parameters at the well mouth there is no expansion in the steam turbine and the scheme becomes identical to fig. 2. If the pressure (and the corresponding temperature) at the steam turbine exhaust are defined equal to the lowest temperature in the bottom cycle (close to the ambient temperature), the power will be produced only by the steam turbine. Strictly speaking the bottom cycle can produce some power even in this case using the heat of the separated geothermal water. However when there are temperature limitations due to precipitation problems the heat content of the separated water is rather low to justify installation of the low boiling turbine.

The mathematical model of the scheme was compiled using the dynamic modeling system TRNSYS, initially elaborated in the USA Wisconsin university (http://sel.me.wisc.edu/TRNSYS/) for modeling solar heating systems. The system consists of a number of FORTRAN modules including modules describing the behavior of scheme components, as well as modules governing the calculation process.

Various low boiling working fluids were considered to study their influence upon the scheme thermodynamic efficiency

- freons (R12 and R134a),
- hydrocarbons (propane, butane, isobutane, pentane, isopentane),
- ammonia.

The optimization procedure with the goal provide for maximum power of the GeoPP was carried out using the pressure at the steam turbine outlet as a main variable. The steam turbine power was calculated assuming its efficiency as 80%. For the bottom cycle the above mentioned low boiling substances were considered. The parameters of the corresponding Rankin cycle as well as the low boiling working fluid specific flow rate were optimized to obtain maximum power from the low boiling turbine. Necessary thermodynamic properties (equation of state, saturation curve, ideal gas thermodynamic functions) of the low boiling fluid were either found in the relevant references, or calculated using some assumptions. As an example a unit for the Verchne-Mutnovskaya GeoPP was considered, which is now in the design stage. Hence the following parameters were regarded as fixed: geothermal fluid flow rate (36,6 kg/s), its temperature 162°C (saturation pressure about 6,5 atm), quality of the two-phase flow (0,3). Fixed were also the geothermal water reinjection temperature (145°C) at the outlet of the heat exchanger V (Fig. 3) and the lowermost temperature (30°C) in the bottom Rankin cycle defined by the air cooled condenser VIII (fig.3).

The optimization results are demonstrated at Fig.4. Here the steam turbine power and the maximum power of the whole GeoPP for each low boiling working fluid are plotted against the exhaust pressure of the steam turbine. The set of curves in the upper part of the graph gives the total GeoPP power for each of the considered low boiling working fluids. The low boiling turbine power can be derived as a difference between those curves and the steam turbine power. As the exhaust pressure of the steam turbine increases the low boiling turbine power increases approaching a maximum value, when the steam turbine power becomes zero.

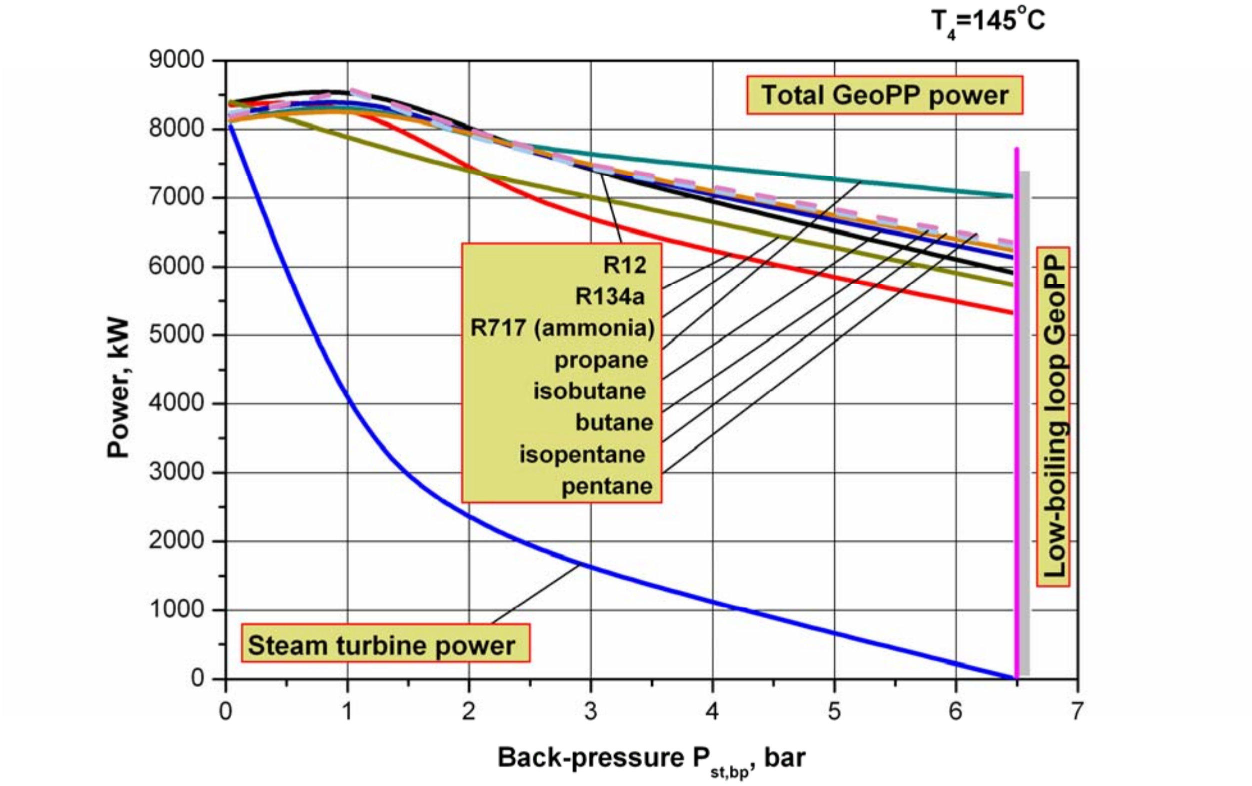

Fig 4. Power of the unit versus back pressure of the steam turbine for a combined geothermal unit to be installed at the Verkhne-Mutnovskaya GeoPP,

Some conclusions can be derived from this example. Maximum power of the unit can be produced by the steam turbine, working alone, with a vacuum condenser. In the back pressure interval 0 – 1 bar the unit total power remains practically constant. A slight power increase can be observed when the back pressure reaches 1 bar. At this pressure the steam turbine power decreases by a half and this decrease is compensated by the low boiling turbine. Above 1 bar back pressure the steam turbine power is dropping rather intensive and in spite of bottom cycle power increase the total unit power is dropping. If the recovered geothermal fluid contains a noticeable amount of steam it is reasonable to use it as efficient as possible. It means that it is reasonable to expand this steam in a steam turbine down to temperature close to ambient depending on the condenser type. In this case for the bottom cycle remains only one energy source namely the separated geothermal water. This energy source is rather scarce, particularly when it is impossible to significantly cool down the separated water due to precipitation problems. It is obvious that in this case the share of the low boiling turbine in the total unit power will be small and there will be no principal difference which low boiling working fluid will be used.

4. Power extraction from hot dry rocks

The heat content of hot dry rocks (HDR) down to depths 5 to 10 km is enormous. To extract this heat it is necessary to create an underground water circulation system using the HDR as a heat exchanger. To maintain the underground flow a system of natural or artificial fractures between injection and recovery wells shall exist. The water is injected from above, heated in the underground heat exchanger and recovered at elevated temperature. The water pressure throughout the flow between the two wells should be some higher than the saturation pressure at the water exit temperature to prevent boiling, which can hamper the flow and the heat exchange process. Hence the specific of HDR systems is that the geothermal heat will appear as a pressurized water flow at elevated temperature. To produce power the heated water transfers its heat in a counter-flow heat exchanger to a working media circulating in a thermodynamic cycle.

Usually defined are the water temperatures T_1 at the recovery well mouth and T_0 at the exit of the power production unit. Thus defined is the specific thermal power carried over by 1kg/s of the water: $N_{th} = 1 \bullet c_{pw}(T_1 - T_0)$, where c_{pw} is the water heat capacity assumed constant in the mentioned temperature interval. There is a theoretical maximum for the specific electrical power N_{max}, which can be produced using the available thermal power N_{th}. Assuming that the geothermal water is cooled down in the power plant heat exchanger at a constant pressure, N_{max} can be calculated as an integral of works produced in a sequence of elementary Carnot cycles operating between current water temperatures T and T_0:

$$N_{\max} = N_{th}[(1 - x\ln(1 + \frac{1}{x})],$$

$$x = T_0/(T_1 - T_0)$$

To approach the theoretical limit it is necessary to choose a thermodynamic cycle with a heat admission curve as close as possible to the water cooling down isobar, and with a heat removal curve as close as possible to the T_0 isotherm. These conditions can be to a certain extent satisfied by a supercritical Rankine cycle. Selecting the thermodynamic cycle one can define the work l, which can be produced by 1 kg of the working fluid. The installation power N is a product $l \bullet w$, where w is the specific flow rate of the working fluid. Hence to maximize N we need to define the maximum w, which can be carried over through the counter-flow heat exchanger under the stipulation that this flow rate is compatible with the selected thermodynamic cycle. If along the heat admission isobar of the cycle the working fluid heat capacity c_{pwm} would be constant, the maximum w could be calculated as

$$w_{max} = 1 \bullet c_{pw}/c_{pwm}$$

However in reality the working fluid heat capacity along the heat admission isobar is not constant making the definition of the maximum working media flow rate more complicated. This issue can be clearly demonstrated for an undercritical Rankine cycle. In this case the heat admission curve has an isothermal evaporation section where the heat capacity is infinite. For the counter-flow heat exchanger defined are the inlet temperatures of the hot water T_1 and of the condensed working fluid T_{wm}. Both outlet temperatures T_0 and T are functions of the flow rate w. When w is quite small $T_0 \approx T_1$ and $T = T_1$. With increasing w the temperature T_0 decreases however T remains equal to T_1. It means that the selected cycle remains intact. This is valid until w reaches the value w_{pinch}, where in some section of the heat exchanger the water temperature becomes equal to the saturation temperature of the working fluid. (More strictly speaking in this section the temperature head ΔT reaches the prescribed minimum). At $w > w_{pinch}$ the working fluid outlet temperature becomes gradually less than T_1. It means that the thermodynamic cycle will change and in particular its thermal efficiency η_{th} will decrease.

The same considerations are valid for supercritical Rankine cycles. A supercritical isobar in the critical point vicinity has a bend point, where the heat capacity becomes maximum providing for formation of a pinch similar to an undercritical isobar.

Calculations of the maximum installation power N were carried out for undercritical and supercritical thermodynamic Rankine cycles with hydrocarbon working media using the TRNSYS software. When a supercritical cycle was selected the geothermal water temperature T_1 was assumed higher than the working media critical temperature. The calculations demonstrate that N is slightly higher for supercritical Rankine cycles. In both cases maximum N is obtained at working fluid flow rates higher than w_{pinch}.

It is concluded that for each geothermal water temperature a proper supercritical Rankine cycle should be selected and for this cycle an optimum specific flow rate calculated providing for maximum installation efficiency.

5. Case study

During the years 2008-2009 it is planned to install a first in Russia binary GeoPP at the Pauzetskaya geothermal field (Kamchatka). Nowadays at this geothermal field operates a GeoPP with an installed power 14,5 MW. The real power of the GeoPP is 7-7,5 MW. The plant scheme is a simple one. It uses 90 t/h of separated steam, whereas more than 200 kg/s of separated water with temperature about 120°C is not used and drained at the earth surface. 118 kg/s of this water flow is supposed to use as an energy source for a binary GeoPP (Fig.5). According to the separated water salinity it can be cooled in the GeoPP down to 62°C and finally either drained or reinjected.

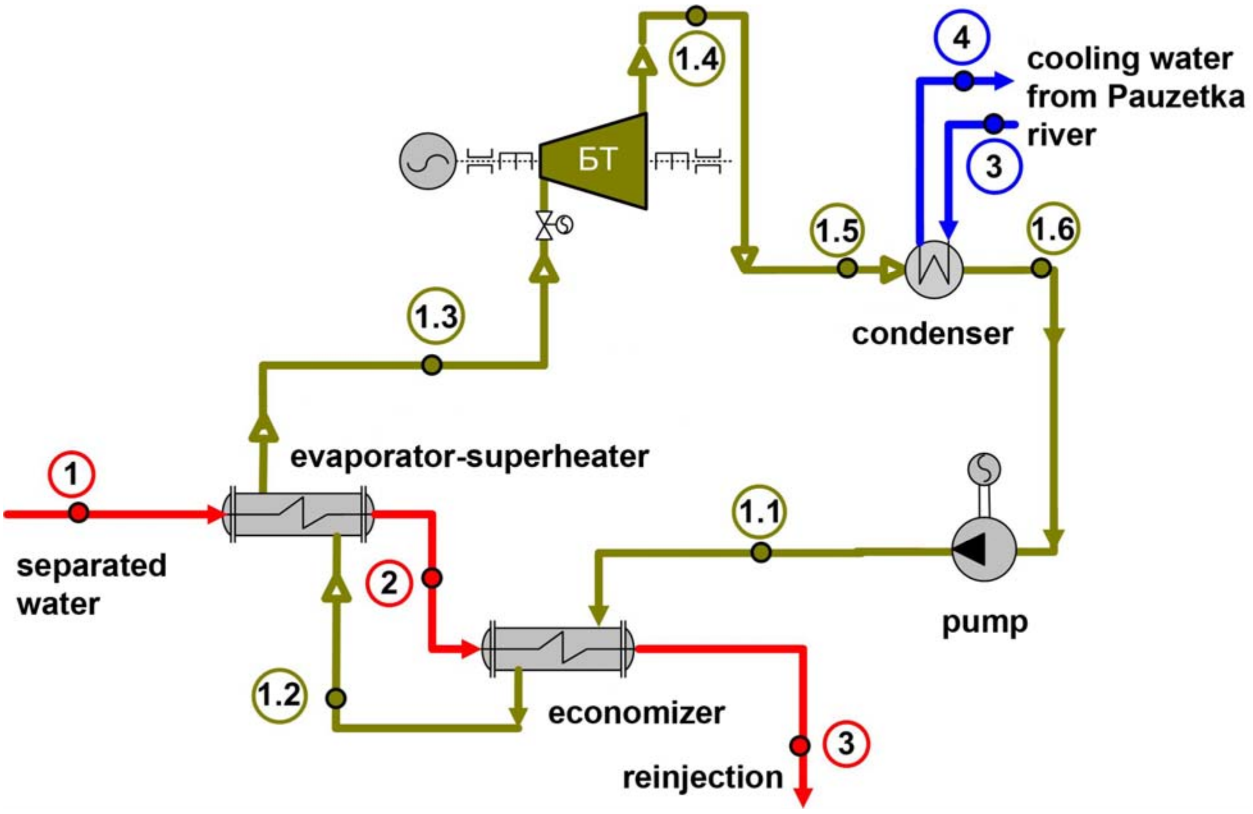

Fig.5. Thermal scheme of the Pauzetka binary GeoPP

The thermal power of this flow is N_{th}=28,65 MW. Calculations using the formula given in the previous section give the corresponding maximum theoretical electrical power N_{el}, which can be produced with this thermal power. Assuming the water temperature at point (1) (Fig. 5) 120°C, at point (3) 62°C, the low boiling fluid temperature at point (1.6) 27°C one can calculate N_{el} = 5 MW. The task is to make the real power of the GeoPP as close as possible to the theoretical value.

The first step is the choice of an optimum low boiling working fluid. Its thermodynamic properties and the corresponding thermodynamic cycle are necessary for the optimization process.. Fig. 6 demonstrates the T,s-diagram of propane and a supercritical (red) and a undercritical (blue) cycle. It can be concluded that propane is not the best solution for the task under consideration. By screening of various candidates as a preliminary solution the Freon R-134a was accepted. The optimization process was carried out using the above mentioned mathematical model and the TRNSYS software. Finally assuming the turbine efficiency $\eta_T = 0.7$ the total GeoPP power was defined as 2.5 MW. Taking into account prasitics the GeoPP net power will be 2,1 MW. This figure may be slightly changed during the design stage.

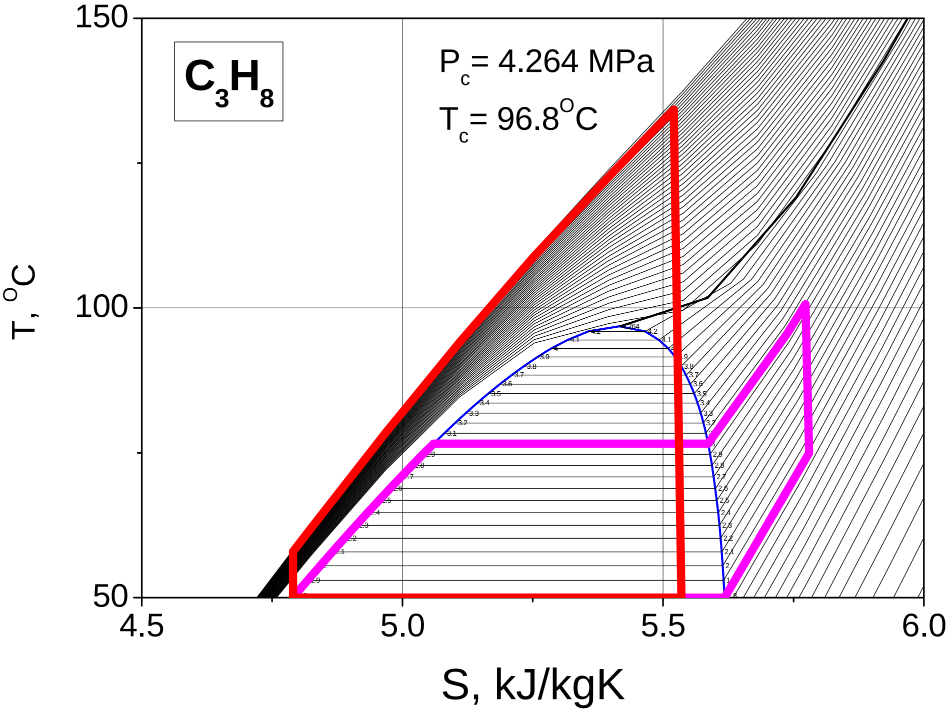

Fig.6. T,s-diagram for propane

The capital cost of the GeoPP was estimated as 270 mln rubles or US$ 11 mln. Hence the specific capital cost will be US$ 5240/kW (net). Assuming operation in base loads regime 7500 h/year the cost of electricity will be some 9 US cents/kwh (net). For the Kamchatka conditions it is quite reasonable. However remind that this GeoPP does not need any underground systems.