Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

OPTIMUM CYCLES FOR GEOTHERMAL POWER PLANTS

Paola Bombarda and Ennio Macchi
Dipartimento di Energetica, Politecnico di Milano, Piazza L. da Vinci 32, 20133, Milano, Italy

Key Words: power generation, binary unit, steam unit, technical-economic analysis

ABSTRACT

The optimum cycle for a geothermal power plant depends on the geothermal brine/steam characteristics and the site features. Selecting the most suitable configuration must therefore be based on the geothermal source and heat reject conditions (i.e. ambient conditions).

This paper investigates the suitable plant configurations for four different kinds of geothermal sources, with increasing enthalpy, going from relatively low temperature (115 °C) liquid brine to high temperature (250 °C) superheated steam, and points out the best solution for each case.

In order to do this, a sophisticated calculation model, which can manage different geothermal fluids, different working fluids and various plant configurations, is employed. The code is capable of optimizing the cycle thermodynamic parameters in order to get the highest economic return. The power conversion cycles considered include the "traditional" flash and binary cycles and the "advanced" combined and mixed cycles, obtained respectively by:

- coupling a flash cycle (topping cycle) with a binary cycle (bottoming cycle)
- splitting the liquid and gaseous content of the source in two separate flows and then feeding a binary cycle with the liquid fraction, and a flash cycle with the gaseous fraction.

The results show the optimum solution for each geothermal resource, the consequent economic return and power produced.

1. GEOTHERMAL SOURCE

In the most general situation the geothermal fluid may consist of a mixture of salty water and steam with noncondensables, and its composition can vary greatly depending on the geothermal field location. The characteristics of the geothermal source are of capital interest in the choice of the best plant configuration and cycle optimization. The major feature is the source cooling curve (i.e. the relationship between temperature and heat released during a cooling process, see fig. 1). Very different cooling curves can be obtained, going from the almost steadily temperature decreasing curve, typical of liquid brine, to the "step" curve of vapor with no noncondensables, characterised by a constant temperature phase change followed by a steadily temperature decreasing curve; in between stay vapor plus noncondensables cooling curves, where condensation occurs at continuously decreasing temperature.

1.1 Geothermal sources selected

Four different resources were used in this analysis, and are identified as follows (see table 1 for details):
A - liquid brine, low temperature
B - low steam quality, low-medium temperature
C - medium steam quality, medium temperature
D - superheated steam, high temperature
Note that the brine enthalpy increase from case A to case D. The mass flow is calculated such as to give the same ideal thermal input in all cases, with reference to a common discharge temperature of 70°C. It is generally assumed to reinject the brine after use, while the noncondensables are released into the atmosphere.

2. PLANT CONFIGURATION

The geothermal resource can be exploited according to two different fundamental schemes: (i) direct cycle: the fluid is sent directly into a steam turbine - also called flash cycle – (ii) indirect cycle: the fluid is used as a heat source for a separate closed power conversion cycle, called binary cycle.
Flash and binary cycles are widespread employed; however, the most comprehensive option for a power plant configuration includes the joined utilization of both fundamental power conversion cycles so as to give "advanced" cycles (mixed and combined cycles). Plant configurations of the cycles considered are represented in fig. 2.

2.1 Flash cycle

The flash cycle is the simplest cycle that can be conceived and is particularly suited for a source with a significant gaseous content (steam and possibly noncondensables).

<u>Basic components</u>
A simple steam turbine is enough to produce power, but other components (flash chambers, condenser, gas compressor) are usually present to enhance power production. It may be helpful to recall briefly the reasons for adopting these auxiliary components:

(i) liquid-steam separator: water fraction must be removed from the mixture prior to send it to the turbine so as to avoid damage to the turbine
(ii) flash chamber: if the initial water percentage is high, and temperature and pressure suitable, it is worthwhile to flash the brine, thus sending to the turbine a greater gaseous flow, though with a lower pressure. If the brine temperature and pressure are adequate, a double flash cycle may be adopted; the medium pressure steam from the second flash chamber is then injected into the turbine at an intermediate stage. From a theoretical point of view, the number of flashes may be indefinitely high, but a solution with more than two flashes is generally not economically viable and was therefore not considered
(iii) condenser: it allows the steam-gas mixture to expand down to a sub-atmospheric pressure and produce more power with respect to atmospheric discharge. For most gas contents and plant sizes, the condenser adoption is advantageous; it becomes mandatory when it is required to reinject the brine. The condenser can be a direct contact condenser, if cooling water from tower is available, or an air condenser in the opposite case
(iv) compressor (or ejector or vacuum pump): if the condensation pressure reaches sub-atmospheric values, it is then necessary to employ a device in order to extract the noncondensables from the condenser and finally release them into the ambient or reinject them together with the brine. In order to be well suited for

geothermal fluids with a not negligible noncondensables content, an intercooled centrifugal compressor was considered (Berton, 1995)

Operating parameters

Flash and condensation pressures have a relevant impact on plant performance and economics and must be therefore optimized as a function of the peculiar plant ambient and economic constraints.

2.2 Binary cycle

The binary cycle consists of a closed cycle, which uses an organic compound as working fluid (Organic Rankine Cycle - ORC). It receives the input heat from the geothermal fluid and releases the output heat into the ambient: it is therefore generally suited with brines that cannot be sent directly into the steam turbine. As discussed later, the introduction of heat in the power conversion cycle is a very significant matter that can imply the adoption of saturated, superheated or recuperative cycle.

ORC working fluid selection

The working fluid must be selected according to its critical temperature, which must be suitable for the temperature level of the geothermal source (see for example Angelino et al.(1995) and Invernizzi and Bombarda (1997) for more details). The choice is restricted by the well known harmful effects of CFCs, which demand the adoption of either hydrocarbons or new fluids recently developed. In the present paper several fluids (R134a, R236fa, R245fa, iso-butane and n-pentane) were considered so as to match each of the different geothermal sources considered (see table 2 for details.).

Cycle organization and basic components

The cycle is characterized by the adoption of an organic fluid turbine, a feed pump and several heat exchangers. Cycle organization depends basically on heat exchanger arrangement. The examination of figure 1, representing two significant examples of the T-Q (temperature versus exchanged thermal power) diagram may be useful to discuss the optimum cycle organization. In part A graph, a high temperature saturated steam with no nocondensables is coupled with a saturated subcritical simple cycle and the two corresponding cooling and heating curves are both characterized by a constant temperature heat exchange followed by variable temperature heat exchange. In part B graph, a fluid composed by a liquid fraction and a gaseous fraction including noncondensables is split in parallel to feed the same simple cycle under the assumption of common discharge temperature: both cooling curves are characterized by a variable temperature cooling. However, in one case the cooling curve is a straight line, while in the other case it is a smooth curve.

In order to match the heating curve of the working fluid and the geothermal fluid cooling curve, it can be argued that:

i. with totally liquid brine and when the fluid contains superheated steam with a high percentage of noncondensables, a superheated cycle can match the brine cooling curve better than a saturated cycle
ii. if the fluid contains steam without or with a few noncondensables, and its temperature is high, the saturated cycle allows an adequate cooling of the source. With low temperature fluids, a recuperative cycle performs better: the best configuration is obtained when the working fluid is fit to receive at constant temperature an amount of heat approximately equal to the quantity released at constant temperature by the geothermal fluid (i.e. when the evaporator is fed by the condensing steam and the preheater by the cooling condensate)
iii. if the fluid is a mixture made of liquid, steam and noncondensables, the solution here considered corresponds to the separation of the liquid and gaseous flows. Again a situation similar to case (i) occurs, but two parallel sequences of counter-flow heat exchangers are employed. The working fluid flow is split after the feed pump into two parallel streams that are joined again before entering the turbine: the evaporation temperature must therefore be the same for both streams.

The cycles selected for each source considered are presented in table 3.

Operating parameters

Together with working fluid selection and cycle arrangement, evaporation and condensation pressures are determinant for the plant performance: they affect the source exploitation, the thermodynamic cycle efficiency, the component size and plant economic performance. In case iii (liquid and gaseous streams) the value of the evaporation temperature is a compromise deriving from the liquid and steam plus noncondensable features. The T-Q diagram and the geothermal fluid discharge temperature cannot in fact be optimized for both streams, and this may result in a poor performance. In such extreme cases it may be better to utilize either of the streams alone.

2.3 Mixed cycles

Mixed cycles are justified by a drawback of flash cycles: these are in fact characterized by a rather simple and low cost plant, but imply intrinsically a partial use of the geothermal source. Just the gaseous phase is in fact exploited, while the remaining liquid phase is discharged without any utilization. More "source exploitation intensive" solutions may be obtained by coupling direct cycles with ORC cycles. The mixed cycle is the most simple solution: the fundamental idea is to split the geothermal fluid flow into two separate flows, and to use the liquid fraction to feed a binary cycle, while sending the gaseous fraction directly to a steam turbine. Being the binary cycle fed by a fully liquid source, a superheated cycle is usually selected. The two plant sections are in this way completely independent; a tighter integration is possible if the steam quality is low and flash processes are employed.

Operating parameters

The key thermodynamic parameters are obviously constituted by the key parameters of both flash and binary cycle. Their optimized values depend on the plant integration: they reduce to the two separate plant optimized values in the most simple condition (no flash processes), but must otherwise consider the influence of flash pressures on both cycles (a low flash pressure reduces both temperature and mass flow available for the ORC cycle).

2.4 Combined cycles

In the combined cycle the direct flash cycle constitutes the "topping cycle" and the ORC cycle the "bottoming cycle". With this solution the steam turbine expansion ends at a pressure slightly higher than the atmospheric pressure: the two cycles are then “joined” by the steam condensation process which provides low temperature input heat for the binary cycle. The corresponding plant scheme is characterized by the adoption of an ORC recuperative cycle and the presence a single heat

exchanger (or heat exchanger series) which performs as condenser for the direct cycle and as the primary heat exchanger for the organic fluid cycle. No gas compressor or ejector is needed to handle the noncondensables, which, having a pressure greater than the atmospheric pressure, can be easily released into the ambient.
The full exploitation of the geothermal source can be attained if the ORC cycle is fed also by the liquid fraction that is otherwise useless discharged. Being the additional power produced by liquid the flow much lower than the base power, it can be shown that no real benefit is generally attainable (Bombarda, 1998). The only exception is represented by the case in which the liquid flow rate is large enough to justify the adoption of a completely separate binary plant (see for example Cole, 1998)

Operating parameters
Like in mixed cycles, the key thermodynamic parameters are still constituted by the key parameters of flash and binary cycles. Flash pressures must be adequate in respect of the imposed nearly atmospheric end expansion pressure (they do not influence the binary cycle, except for the ORC mass flow).

3. HEAT REJECTION INTO THE AMBIENT

Regardless of the cycle adopted, the output heat must be discharged into the ambient: this may be accomplished either by water condensation or air condensation. From a thermodynamic and economic point of view, the first option generally constitutes the most favorable situation: it allows a lower condensation pressure and a lower auxiliaries power and is normally achieved with cooling water from wet tower. In the present work it is assumed that make up water for the tower comes from the liquid fraction of the source (i.e. no employment of fresh water outside the geothermal source is considered). Water condensation is therefore feasible whenever enough water is available to compensate for the evaporation and blowdown loss (this last one depending on initial brine salt concentration and maximum salt concentration allowed in the cooling loop).
The ambient conditions are characterized by a dry bulb temperature of 26 °C and a wet bulb temperature of 20 °C and are regarded as medium seasonal values.

4. MODEL DESCRIPTION

The model utilized (Bombarda et al., 1998) was developed in the frame of a long research cooperation conducted with ENEL, the Italian Electric Board. The computer code used is made of several programs implemented together, which include numerical optimization procedures, each one aimed at a different aspect of geothermal power plant design. The main areas covered are: thermodynamic calculation, detailed component design and economic optimization.

4.1 Thermodynamic properties

Geothermal source
The model assumes that salts are entirely contained into the liquid phase, either dissociated in the solution, up to a maximum solubility limit, or precipitated, in case they overcome this limit. The noncondensables (considered as constituted by CO_2, which is the most common situation) are regarded as forming an ideal mixture with the vapor. The thermodynamic properties of the mixture depend therefore both on salt content and noncondensables mass fraction. A numerical procedure, aimed at reproducing the steam tables of Schmidt (1982) was extended in order to include the effect of noncondensables and salts (Duvia, 1998).

Organic fluid
The thermodynamic properties of the organic fluid are obtained by the ideal gas properties and a proper equation of state (Bombarda et al. 1998)

4.2 Steam cycle

The crucial point of steam cycle calculation is the reconstruction of the expansion line. The steam turbine model is derived from a model utilized for bottoming steam cycles (see Lozza, 1990) whereby the expansion is calculated stage by stage, referring to similarity considerations. The model accounts for stage specific speed, volume flow rates, leakage, presence of liquid and kinetic energy loss at discharge. A similar approach is used for computing the performance of centrifugal compressor. Bearings, generator and all other minor auxiliaries consumption is properly accounted for.

4.3 Binary cycle

The key points for an optimum cycle design and evaluation include turbine efficiency estimation and sizing and assessment of heat exchangers performance, which play a determinant role in the overall cycle performance.
Heat exchange coefficients and pressure drop in heat exchangers are evaluated whenever needed on the basis of the most reliable correlations available in literature. The high molecular weight of the fluid employed in ORC cycles permits the adoption of a single stage turbine, which is assumed to work at optimum specific speed: following Macchi and Perdichizzi (1981), the stage efficiency is then evaluated as function of the size parameter with a correction factor accounting for the effect of the expansion ratio. Similarity considerations are invoked also to determine the pump efficiency; it is to underline that, depending on the fluid used, feed pumping power may constitute a not negligible fraction of the turbine gross power. Bearings, generator losses and other auxiliaries consumption are then estimated as a function of gross power.

5. TECHNICAL ECONOMIC ANALYSIS

Several economic indicators exist to state the convenience of a considered investment: the most commonly used are the Net Present Value (NPV), the Internal Rate of Return (IRR), and the Pay Back Time (PBT); among them the IRR was chosen as the objective to be maximized in this work. It is to point out that the choice of one indicator in respect to others may lead to a rather different optimum solution. It must also be stressed that the choice of the net power produced as the object to be maximized would lead to even more different solution, i.e. the choice of IRR as the objective does not generally correspond to maximum power obtainable.

5.1 Basic assumptions

Two kinds of economic assumption are needed in order to proceed with the analysis: the first group concerns the economic general parameters, the second one the various component costs. The following assumptions were chosen:

General economic parameters
- plant lifetime: 15 years

- yearly operating hours: 7500 hours/year (base load operation)
- interest rate: 2.5 % above inflation
- electrical energy price: 0.0387 euro/kWh. Care must be always taken in considering this value, which can vary greatly from one situation to another. The energy price is the result of a lot of circumstances (market conditions, possible monopolies, etc.). In the specific case of geothermal energy it may be altered by particular favorable conditions or incentives for renewable energy.
- geothermal cost: 8 million euro. It represents the sum of the costs related to well drilling (which may be regarded as approximately proportional to the well depth, see Bottomley and Grant, 1998) and geothermal field preparation. It depends significantly on local conditions and it has a heavy influence on the optimum solution: if the geothermal cost is high, the optimum solution will be complex and expensive but will enable a great power output (for more details see Bombarda, 1998). The adoption of a quite high value, like the one here considered, may be representative of the exploitation of deep geothermal resources.

Plant and (O.&M.) cost

The evaluation of the plant cost requires the sizing of every major component. Note that a maximum value for the sizing of the components exists and it sometimes happens that several identical ORC modules in parallel are required.

Costs are estimated basically by means of a linear rule, which gives the component cost as the sum of a fixed cost plus a variable cost, the latter being proportional to a peculiar dimension or characteristics of the component considered. The particular values adopted are, except minor changes which appeared recommended, the same as the ones reported in Bombarda (1998). The total plant cost is finally estimated by adding a fixed amount corresponding to balance of plant cost (B.O.P.).

Operating and maintenance costs (O.&M.), both fixed and variable, are assumed equal for steam and ORC section. If both sections are present, fixed maintenance costs will be therefore double with respect to simple binary or flash cycle.

6. DISCUSSION OF RESULTS

The results obtained from calculations are presented in figure 3. The discussion will be carried on examining the following parameters:

- the geothermal brine discharge temperature (fig. 3A); this temperature gives an indication of how much the geothermal source is exploited, even if does not give information about the energy conversion efficiency. Note that for a binary cycle this temperature concerns the whole of the source mass flow, while for other cycles it regards only the liquid fraction which is discharged after the last flash process. The vapor fraction, which is condensed after the expansion, attains a much lower value (corresponding to the condensation pressure)
- the specific investment cost (fig. 3B): it includes the geothermal cost, which has a different impact according to the power produced
- the net plant power and electrical efficiency (fig. 3C), defined as the ratio between the net power produced and the ideal thermal power of the source
- the internal rate of return (fig. 3D).

Note that in the first two cases, A and B, water condensation is feasible, while for the last two cases, C and D, air condensation is unavoidable. With reference to the selected geothermal sources A,B,C,D (see table 1) we can observe that:

- with a geothermal source of type A (low temperature liquid brine) the binary cycle has the best global performance: it attains a low discharge temperature (very close to the limit value of 70°C) and gives power with a convenient cycle efficiency, allowing the highest IRR. The optimized configuration of flash cycle adopts a single flash chamber and benefits from the low cost of direct contact condenser in respect of the binary cycle; however the specific investment cost is still higher and the net power produced lower, resulting in a poorer IRR. The mixed cycle is characterized by the best source exploitation and can achieve the greatest power but with high investment and maintenance costs, resulting in a IRR similar to that of the flash cycle. The combined cycle is not adaptable to low temperature liquid sources
- with a geothermal sources of type B (liquid and gaseous fractions, with low steam quality) both streams are profitably used to feed the binary cycle, but this implies a quite high discharge temperature and a high investment cost, and does not allow to reach high net power and IRR. The optimum plant configuration of flash cycle consists of a simple liquid-steam separator followed by a flash chamber. Though the discharge temperature is quite high, the net power produced is high and the specific investment cost the least of all, so as to give the best IRR. The mixed cycle continues to allow the best source exploitation (minimum discharge temperature) and exhibits the greatest power, but the higher maintenance cost nullifies the thermodynamic advantage over the flash cycle, resulting in a similar IRR. The combined cycle reaches the minimum discharge temperature as well, but it is hindered by the heat rejection process in the ORC cycle, resulting in a higher investment cost and a lower power than the flash cycle
- with a geothermal source of type C, (liquid and gaseous fractions, with high steam quality) the binary cycle utilizes the gaseous stream alone, which allows the attainment of minimum discharge temperature. All the cycles which include the steam section, though presenting different discharge temperature, give similar global results. A major effect is due to air condensation: flash and mixed cycles are characterized by a higher condensation pressure and exhibit a moderate increase in net power and a lower IRR than in the previous case B. The combined cycle gives the highest power and IRR (this last one is almost equal to the IRR of flash cycle: the slightly lower investment cost is counterbalanced by the higher maintenance cost)
- for the last case D (steam with noncondensables), the binary cycle is hindered by the not negligible noncondensable content. The flash cycle exploits the whole source flow without any flash process but the preeminence of the combined cycle is now evident: the total source flow is exploited, the minimum discharge temperature is attained, the highest power is produced, the investment cost is the lowest, and therefore the highest IRR is attained. The mixed cycle does not apply when no liquid flow is available to feed the binary cycle.

7. CONCLUSIONS

The analysis conducted has pointed out the best plant

configuration. The best solution depends upon the source characteristics. As a general rule the net plant power and economic return increase with the thermodynamic quality of the source.
The binary cycle, which is well known as the best solution with low temperature liquid brine, exhibits in this case the best IRR, though the mixed cycle is slightly better as far as power is concerned. With low steam quality the flash cycle and mixed cycle exhibit almost the same IRR, but again the mixed cycle is characterized by a greater power. With medium-high steam quality and with air condensation the combined cycle emerges as the most profitable solution: "advanced" cycles are hence very promising alternative to the "traditional" binary and flash cycles, though the mixed cycle is somewhat hindered from high investment costs.
It is important to stress that the best economic solution does not usually correspond to the greatest power obtainable, and therefore an increase in power production is still possible. This increase could be also convenient from the economic point of view under different economic constraints (e. g. a higher geothermal cost or electrical energy valorization).

ACKNOWLEDGEMENTS

The simulation model here employed derive from a research cooperation carried on with the Italian Electric Board ENEL.
The authors are also grateful to Ing. A. Duvia for his help in performing calculations.

REFERENCES

Angelino G., Bini R., Bombarda P., Gaia M., Girardi P., Lucchi P., Macchi E., Rognoni M., Sabatelli F., (1995). One MW binary cycle turbogenerator module made in Europe. Proceedins of "*World Geothermal Congress*", Florence,

Berton M., (1995) "Turbocompressors for geothermal plants", Proceedins of "*World Geothermal Congress*", Florence , pp.2081.-2087

Bombarda, P., Duvia, A., Macchi, E., (1998). Combined, Mixed and Binary cycles for electricity Generation from Geothermal Sources - part A: selected configurations and calculation model. Proceedings of "*The 20th New Zealand Geothermal Workshop*", Auckland, pp. 347-352.

Bombarda, P., (1998) "Combined, Mixed and Binary cycles for electricity Generation from Geothermal Sources - part B: technical economic analysis ", Proceedings of "*The 20th New Zealand Geothermal Workshop*", Auckland , pp. 353-358.

Bottomley J., Grant M., (1998) "The economics of production from deep geothermal resources", Proceedings of "*The 20th New Zealand Geothermal Workshop*", Auckland, pp. 191-196

Cole B., (1998), "Geothermal energy powers New Zealand" *Modern Power Systems*, pp.21-24

Duvia, A., (1998) "Technical Economic Analysis of Geothermal Cycles", *Graduation Thesis*, Politecnico di Milano, Italy (in Italian)

Invernizzi, C. Bombarda, P., (1997) "Thermodynamic performance of selected HCFS for geothermal applications", *Energy*, vol. 22, n°9, pp. 887-895

Lozza, G., (1990) Bottoming steam cycles for combined gas-steam power plants: a theoretical estimation of steam turbine performance and cycle analysis. Proc. *1990 ASME Cogen Turbo* (New Orleans, Luisiana), pp. 83-92

Macchi, E. Perdichizzi, (1981) A., Efficiency prediction for Axial -Flow Turbines Operating with nonconventional fluids, *Journal of Engineering for Power,* vol 103., pp.718-724

Schmidt, E., (1982) Formulation and equations. In *"Properties of steam and water in SI units*", Springer-Verlag, pp. 179-194

Table1 Thermodynamic characteristics of the selected brine (x= steam quality, y mass fraction of noncondensables). Salt concentration in all cases: 0.5 mol/kg. (maximum concentration allowed 1.5 mol/kg). The ideal thermal power amounts to 128.9 MW.

	p (bar)	T (°C)	x	y	m(kg/s)	h(kJ/kg)
A	5	115	0	.0013	671.8	486
B	5	152	0.25	.01	148.5	1165
C	12.5	190	0.6	.01	76.1	1994
D	25	250	1	.05	52	2750

Table 2 Organic working fluid selected for the ORC cycle according to the geothermal source and plant configuration. R236fa was also considered but never selected. Note also that for source D, combined cycle, the adoption of n-pentane could be considered as well (it would allow a greater power than iso-butane, though with a lower IRR).

	binary	mixed	combined
A	R134a	R134a	-
B	R245fa	R134a	iso-butane
C	n-pentane	n-pentane	iso-butane
D	n-pentane	-	iso-butane

Table 3 Thermodynamic cycle selected for the ORC section according to the geothermal source and plant configuration.

	binary	mixed	combined
A	superheated	saturated	-
B	superheated	superheated	recuperative
C	saturated	superheated	recuperative
D	superheated	-	recuperative

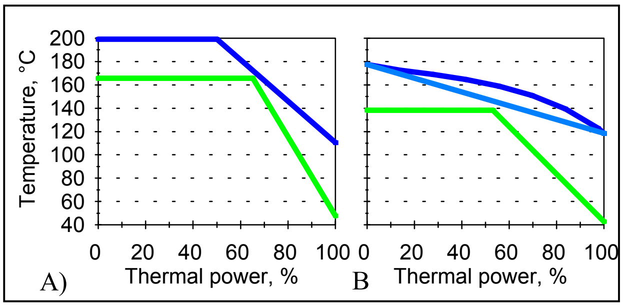

Figure 1: Significant examples of T-Q diagrams: the cooling curve of the geothermal source (dark line) is plotted together with the heating curve of the ORC working fluid (light line). In case A saturated geothermal steam is considered; in case B double phase geothermal source is examined; in both cases saturated cycle is assumed.

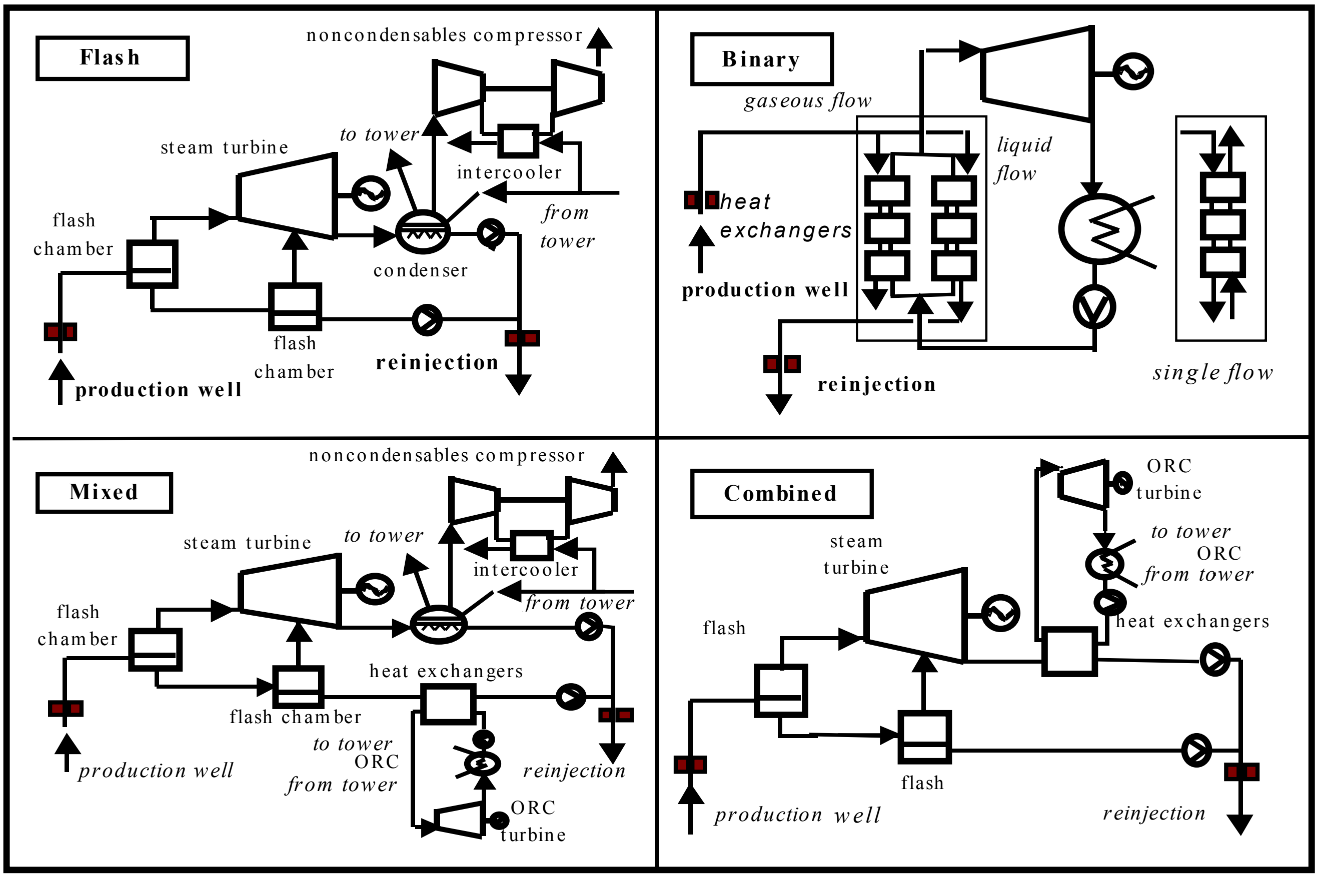

Fig.2 Plant configurations

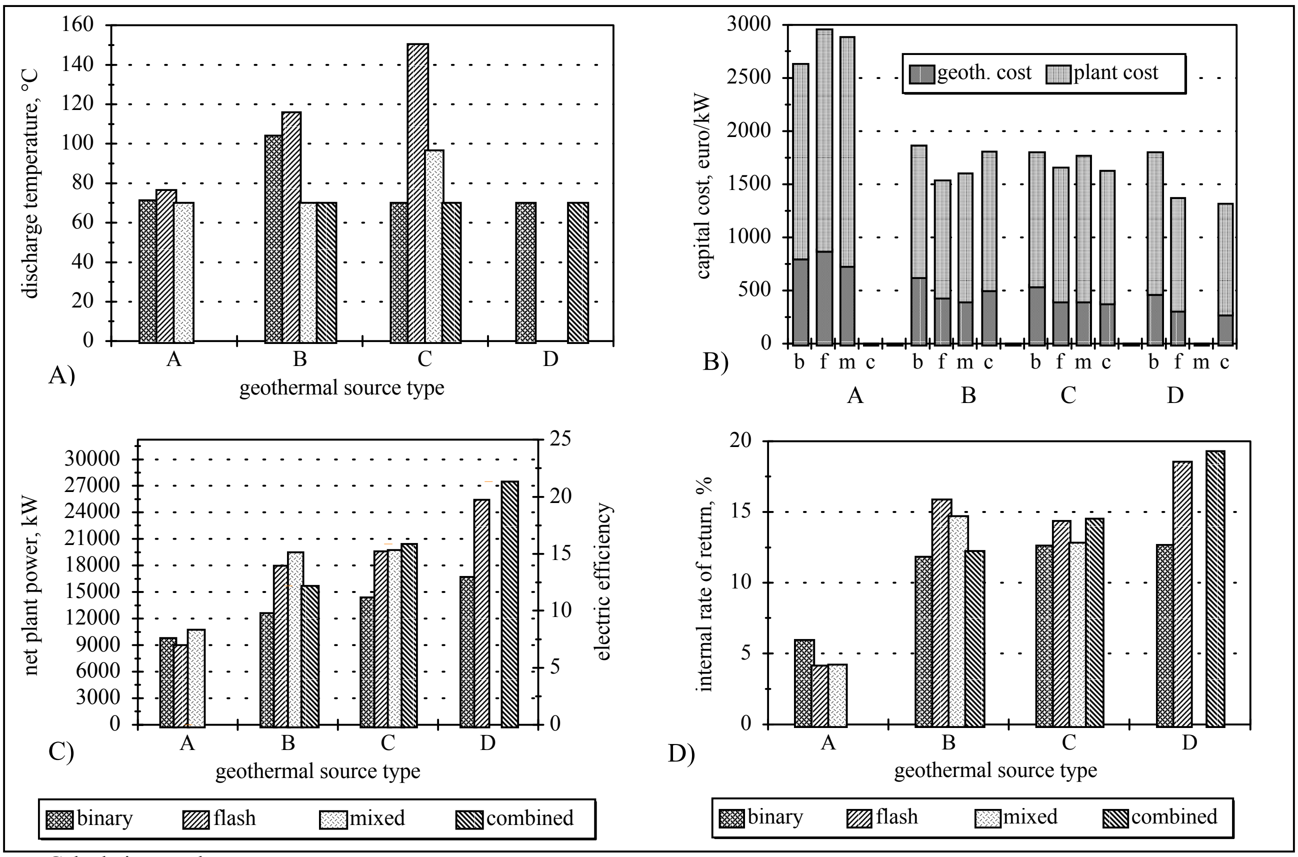

Fig. 3 Calculation results.