Geothermal Binary Plants Utilising an Innovative Non-Flammable Azeotropic Mixture as Working Fluid

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GEOTHERMAL BINARY PLANTS UTILISING AN INNOVATIVE NON-FLAMMABLE, AZEOTROPIC MIXTURE AS WORKING FLUID

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SUMMARY Several attempts have been made to use a non flammable fluid as a working fluid in geothermal binary systems. The adoption of a non-flammable fluid is in particular interesting when the geothermal plant has to be located in a densely populated area, where it can be difficult to stay away from buildings and other infrastructure. A flammable fluid involves in any case a higher cost of insurance and of safety systems. Other requirements for the working fluid are a suitable thermodynamic behaviour, chemical stability, acceptable toxicological and environmental properties, including zero-ODP (ozone depleting potential) and low GWP (global warming potential). The potential use of a mixture of two well known fluids, respectively an HFC and a Perfluoro-poli-ether, exhibiting azeotropic behaviour, is analysed in the paper from the performance point of view, adopting economically optimised heat exchange surfaces. As reference geothermal fluid a liquid-only flow was assumed, with temperatures in the range from 105 to 180 deg C. The described working fluid has been successfully adopted as a substitute for a Perfluoro-carbon in the low temperature geothermal binary plant of Altheim, Austria. The experimental results, as well as the analysis implemented in the paper, indicate that this fluid could be a very interesting alternative to the hydrocarbons widely used at present in geothermal binary plants.

1. INTRODUCTION

The reasons which have led to the growing success of the binary plants for geothermal applications are well known and they will be here very shortly outlined. As a first, obvious advantage, in a binary plant the geothermal fluid does not contact the turbine, which is not subject to the severe scaling, corrosion and erosion problems of flash steam turbines. Moreover, if the geothermal fluid is kept in liquid state, the salt content is not influenced by flashing, hence the scaling problems are reduced, both on the surface and down-hole. The binary plant turbines are much smaller in diameter and stage number than their steam counterparts. The geothermal fluid in a binary plant is confined in a small part of the plant and it is easy to avoid fluid dispersion in the environment and to inject the geothermal fluid underground.

At present the most appealing application, at least in Europe, seems to be the exploitation of liquid geothermal fluids, characterized by a set of temperature, gas content and pressure values which prevent flashing at any point in the plant. This approach reduces drastically the power required for the re-injection of the geothermal fluid, the scaling problems, the number of interacting components on the surface (vessels, separators and mixers, rotating machines, piping connections). The geothermal fluid can be either natural or artificially produced/ enhanced by some sort of rock fracturing, up to the limit of a pure Hot Dry Rock (HDR) concept. A well known and extremely interesting case is exploitation of the Soultz field, which will start producing electricity in 2007. Being Europe, in some cases future plants could be unavoidably located in densely populated areas, thus causing increased safety problems.

The geothermal source is characterized by its temperature, pressure, fluid composition and gas content. The most important parameter for binary plant efficiency is the temperature, which will be taken as a key variable in the present paper. Attention will be focused on a 1 MW power plant. The required geothermal fluid flow will be varied accordingly, supposing that no limit for the well exists (in real cases, the available flow will be determined by the characteristics of the field and of the well system). With the aim of a reduced environmental impact, it is assumed that the geothermal fluid is fully reinjected after use (this fact has also a beneficial effect on the reservoir exploitation); for the same reason air condensation, either direct or indirect, is selected as ambient heat rejection mode. A recently introduced, non-flammable working fluid, known under the brand name Solkatherm (Solvay) is selected as potential working fluid, and compared with the widely used isopentane fluid.

2. BINARY PLANTS OPTIMIZATION

Basically there are three options for the efficient use of all liquid, gas containing sources in a binary system:

(i) the "low pressure" ORC concept, utilising a working fluid condensing at a pressure not far from the atmosphere pressure and evaporating far below the critical pressure

(ii) the "high pressure" ORC, utilising a working fluid at a pressure not far from the critical pressure (either sub-critical or higher then critical)

(iii) the Kalina Cycle, in its various forms.

The solutions (ii) and (iii) involve high speed turbines, more sophisticated controls and higher feed pump pressure and power than (i). Hence solution (i) is generally considered preferable, at least in the 1 MW electric power range, and the present study is focussed on this solution, only.

With reference to the "low pressure ORC", different plant performance, as far as power production is concerned, can be obtained, depending on the good matching between the heat release curve of the heat source and the heat receiving curve of the working fluid. If the two curves are well matched, then the temperature difference will be everywhere limited, the generated entropy will also be low, and the power produced will be high, provided the other cycle components perform equally well. In this context, the choice of the cycle working fluid is of paramount interest: the heat receiving curve is in fact specific of the considered working fluid. The size of the heat exchangers is an important variable; for every working fluid selected, evaporation and condensation temperatures must be optimized in order to allow the best possible heat exchange curve matching. Hence the final comparison must take into account the costs of the whole system, balanced against the power production. Moreover for a complete and fair comparison the externalities should be taken into account, too. The heat sink is also considered in the optimization process, as the positioning of the evaporation and condensation temperatures depend on both heat sources.

The present work can be considered as a preliminary step, taking into account a saturated cycle and the costs of the most important items (see table 4 in the following sections). The performance of optimized Solkatherm cycles will be compared with the performance of optimized isopentane cycles.

3. SOLKATHERM

Solkatherm (brand name of the manufacturer of the fluid, Solvay) is an azeotropic mixture of 65% of a hydrofluorocarbon, R365mfc (1,1,1,3,3-Pentafluorobutane) and of 35 % of a perfluoro-poli-ether (Galden HT55). The main characteristics of this fluid and of isopentane are compared in Table 1. A more comprehensive series of thermophysical properties of Solkatherm can be found in (Fröba *et al.* 2005); a review of possible Solkatherm applications is conducted in (Riva *et al.*, 2006)

Table 1 Comparison between Solkatherm and isopentane. (*) Saturated values refer to 25°C for Solkatherm and normal boiling point (27.85 °C) for isopentane.

		Solkatherm	**Isopentane**
Molecular mass		184.45	72.15
Critical temp.	*°C*	177.4	187.25
Critical pressure	*bar*	28.4	33.8
Normal boiling point	*°C*	36.7	27.85
Density, saturated liquid (*)	*kg/m^3*	1363	613
Density, saturated vapour (*)	*kg/m^3*	5.8	3.07
Heat of vaporization (*)	*kJ/kg*	117.8	341.9
Specific heat capacity(*)	*kJ/kgK*	1.32	2.29

The rationale for considering Solkatherm as an interesting working fluid, besides being non-flammable and non-aggressive to the metals used in the heat exchangers, include mainly the advantage of a high molecular mass, combined with relatively favourable transport properties. The flammability aspect may be secondary in many geothermal installations, typically having ample space available for the well-head equipment, the receiving vessels/lagoon, and the power generation equipment. In all those cases the advantage of non-flammability is limited to the reduction of cost of some items (electric equipment, like motors, generators and valves) and possibly to a reduction of the insurance costs. It can however become more relevant in an installation in densely populated urban areas, as in the case of Altheim, Austria, (Fig.1 and Table 2) where Solkatherm has been adopted for the first time as working fluid by Turboden Italy.

Fig.1 Turboden ORC plant using Solkatherm in Altheim, Austria.

Table 2 Main characteristics of the Altheim power plant

Source inlet temperature	*°C*	106
Source discharge temperature	*°C*	70
Source mass flow	*kg/s*	81.7
Electric power	*MW*	1
Generator speed	*rpm*	1500
Cooling water inlet temperature	*°C*	10
Cooling water outlet temperature	*°C*	18

The high molecular mass can be considered as an advantage as it involves a very low value of enthalpy drop in the turbine; consequently the turbine can obtain a high efficiency at low peripheral speed, and at a low rotational speed (E.G. allowing the direct coupling to a 4pole electric generator, without the losses of a reduction gear).

4. CALCULATION DETAILS

The model utilized is derived from an existing model (Bombarda *et al.*, 1998) aimed at evaluating the performance of complex geothermal plants. The computer code used is made of several programs implemented together, which include nested numerical optimization procedures, each one aimed at a different aspect of geothermal power plant design. The main areas covered are thermodynamic calculations, component design, and economic optimization. In the case of binary plants, the optimization procedure, aimed at maximizing the internal rate of return, is focused on the determination of the optimized values of evaporation and condensation temperatures; being the heat sources given, this implies the optimum sizing of the primary heat exchanger and heat rejection system.

4.1 Thermodynamic properties

Geothermal source

The geothermal source properties are simply evaluated as a function of temperature, while the salt and dissolved gas content is not taken into account.

Organic fluid

The thermodynamic properties of the organic fluid are obtained by the ideal gas properties together with a proper equation of state; transport properties are calculated on the basis of the methods suggested in (Reid *et al.,* 1988).

4.2 Basic assumptions

Basic assumptions regard geothermal source temperature, heat rejection to the ambient; auxiliary consumption; component costs; geothermal cost.

Geothermal source temperature is considered variable in the range 105°C-180°C. This range includes most promising European geothermal systems like those in the Rhine graben area.

For the heat rejection scheme two different options are considered:
(i) closed loop water condensation with air cooler
(ii) direct air condensation.

Cooling source temperatures are shown in Table 3.

Table 3: Assumed cooling medium temperatures for the condenser.

Refr. fluid	**T_{IN} (°C)**	**T_{OUT} (°C)**
water	16	26
air	11	24

Auxiliary consumption is calculated by considering:

- a fixed fraction (1.5%) of cooling power for the water loop case; fan consumption for the air condenser, evaluated with a fixed air velocity (2m/s) in the finned air condenser and fixed fan efficiency (0.6).
- fixed well pump head (20 bar) and global pump efficiency (0.75); the head value assumed is considered suitable for reinjection in all cases.
- a fixed amount (7 kW) representing all other auxiliaries.

Heat exchangers are assumed to be shell&tube, with the exception of the air condenser, which is a finned tube heat exchanger.

Economic component assumptions are reported in Table 4.

Table 4 Assumptions for the economic optimization; for the heat exchangers cost an overall transformation multiplier coefficient of 1.25 is also assumed.

Item	**material**	**fixed cost**	**variable cost**
		€	*€/kg*
preheater	hastelloy	50000	75
evaporator	hastelloy	50000	75
water cond.	carbon steel	50000	2.75
		€	*€/m²*
air conden.		50000	250
			€/kW$_t$
air cooler		-	40
		€	
turbine and control system		250000	

It is very difficult to estimate the geothermal cost, represented by the exploration, drilling and well construction cost, which is strongly site dependent. The effect of this parameter on the optimization procedure is noticeable if its value is low, taking to an optimized solution with small heat exchangers and high minimum temperature difference in the heat exchangers (hence a small power produced, cfr. cap.2). If the geothermal cost grows higher, as normally happens in today's plants, it brings the optimized solution near the minimum heat exchanger temperature difference allowed; from this point on, its influence is almost only on the plant IRR, and the optimized cycle configuration remains stable. In this work geothermal cost was assumed 3.5 million euro; with the adopted value, the influence on the optimum performance is negligible and it does not influence the comparison of the two working fluids.

The electric energy value, which obviously also influences the optimization procedure, was assumed equal to 0.15 €/kWh, which is a reasonable value for Germany.

5. PERFORMANCE COMPARISON

The evaluated performance of Solkatherm and isopentane were compared from different points of view: (i) plant performance; (ii) cycle optimization; (iii) components.

5.1 Well requirements and plant performance

Being the ORC power assumed equal to 1MW electric, if the fluids have the same recovery efficiency, the same geothermal mass flow consumption is to be expected. The plant performance depends on the auxiliary consumption, which, in turn, depends also on the required geothermal mass flow; a similar situation exists for plant net electric power.

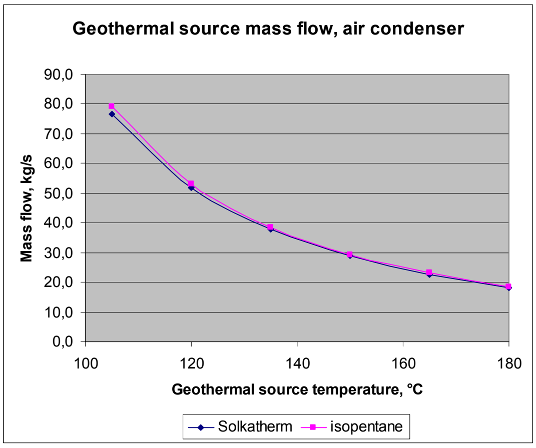


Fig. 2a Required geothermal source mass flow as a function of temperature in order to produce 1 MW electric power, with air condenser;

As far as the geothermal source mass flow is concerned, no real difference exists between the fluids compared in the range of the geothermal source temperature (Fig.2a and 2b) but the required mass flow is strictly dependent on the geothermal source temperature.

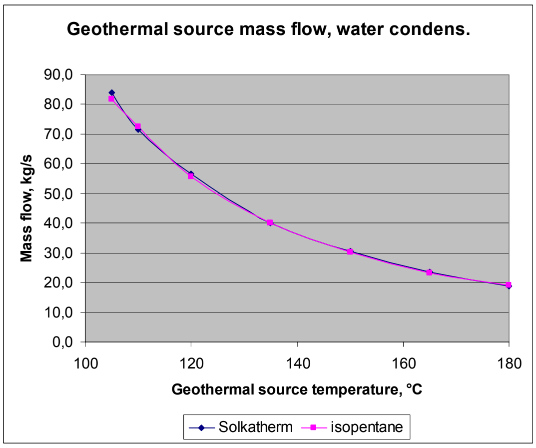
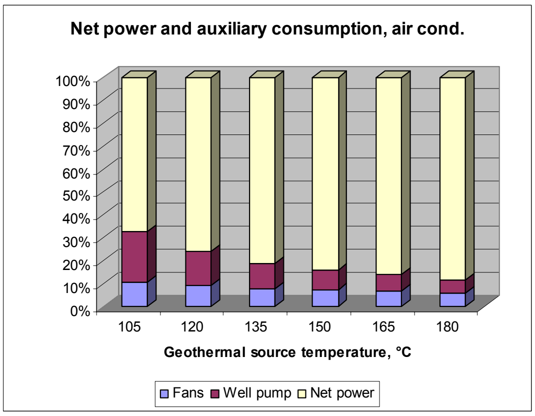


Fig. 2b Required geothermal source mass flow as a function of temperature in order to produce 1 MW electric power, with closed loop water condenser and air cooler.

A slight difference in required mass flow appears between the two cooling options considered; with the assumed values, air condensation allows a slightly lower condensation temperature, therefore a slightly higher cycle efficiency and lower required mass flow.

The net plant power produced is also highly dependent on the geothermal source temperature (see Fig. 3, Solkatherm case).



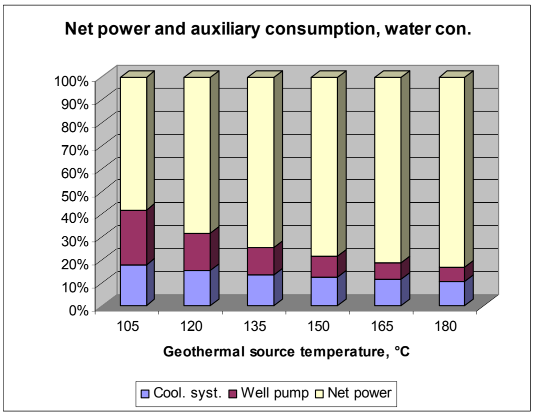


Fig. 3 Net power produced and auxiliary consumption for Solkatherm plant; top: with air condenser; bottom: with closed loop water condenser and air cooler.

The graph shows that auxiliary consumption spans from a minimum value of 10-15% at high geothermal source temperature up to a value of 40 % for low geothermal source temperature. In the case of isopentane (not shown in the figure) the same behaviour is found; a slightly less cooling power than for Solkatherm is required with closed loop water condensation option, and the correspondent auxiliary consumption is also slightly lower (a few percent points)

5.2 Cycle configuration

The optimization procedure identifies the best evaporation and condensation temperatures for all cases, i.e. the best "positioning" of the cycle in T-s diagram.

By examining the optimized values it can be noted that:

(i) the condensation temperature is not influenced by the geothermal source temperature, and depends only the cooling source

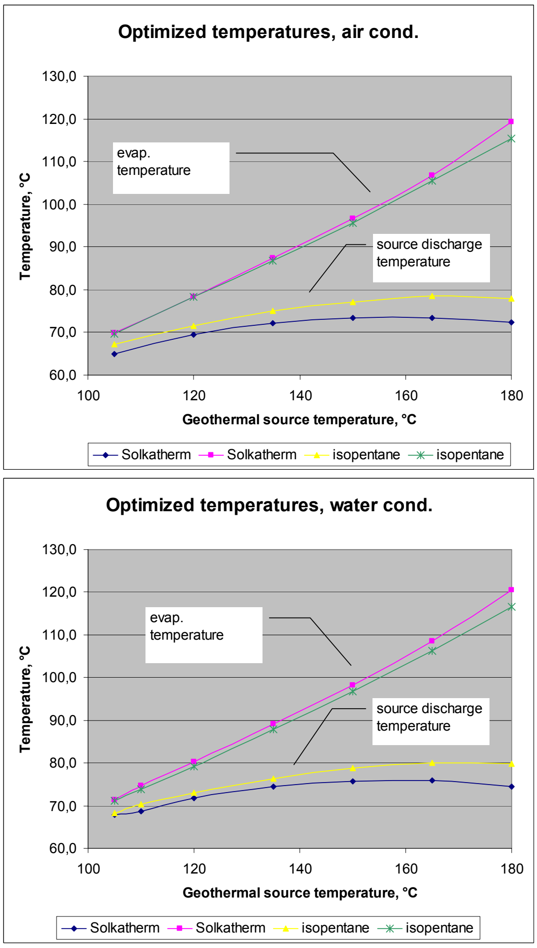


Fig. 4 Optimized evaporation temperatures and geothermal source discharge temperatures. Top: with air condenser; bottom: with closed loop water condenser and air cooler.

(ii) the evaporation temperature depends strictly on the geothermal source temperature, getting lower together with a lower geothermal source temperature; Solkatherm shows always a somewhat higher value than isopentane. Altogether the cycle gets narrower when the geothermal source temperature goes lower

(iii) the discharge geothermal source temperature is always lower for Solkatherm and this effect is particularly noticeable at high geothermal source temperature: in all cases this parameter exhibits a flat maximum in correspondence of a geothermal source temperature equal to 165 °C. The reason for this behaviour lies in the saturation curves and ratios of preheating and evaporating heats of the two fluids.

5.3 Components characteristics

In order to better understand the different behaviour of the fluids, a comparison (table 5 and 6) on the components sizing and performances was conducted assuming a geothermal source temperature equal to 150°C.

As already seen, Solkatherm allows a lower geothermal source discharge temperature than isopentane, and this implies greater thermal power in the cycle; also, since the cycle efficiency is slightly lower (10.5% versus 11.1%) implies a greater discharged thermal power at the condenser. As a consequence, heat exchangers are charged with a thermal power greater for Solkatherm than isopentane. Heat exchange coefficients (**U** in Table 5) are higher for isopentane than Solkatherm and both aspects lead to bigger surfaces (**S** in Table 5) for Solkatherm heat exchangers and hence higher costs. No great difference arises for the turbine, where Solkatherm greater mass flow (48.1 kg/s with respect to 20.7 kg/s) is counterbalanced by a smaller specific volume (0.023 m^3/kg versus 0.054 m^3/kg) giving a similar volumetric flow rate ($\dot{V}_{IN}$ in tables) and similar isoentropic efficiency (slightly higher for isopentane).

Table 5 Solkatherm component characteristics and costs. U heat exchange coefficient, S heat exchanger surface, η isoentropic efficiency, $\dot{V}_{IN}$ turbine inlet volumetric flow

	U	**S**	**Cost**
	W/m^2K	*m^2*	*$10^3€$*
Condenser	640	1775	216
Evaporator	1843	160	300
Preheater	430	344	300
	η	$\dot{V}_{IN}$	**Cost**
		m^3/s	*$10^3€$*
Turbine	0.858	1.13	250
	Cost ($10^6€$)		
Components cost	1.066		
Air cooler	0.338		
Estimated plant cost (with B.O.P.)	1.830		

Table 6 Isopentane component characteristics and costs. U heat exchange coefficient, S heat exchanger surface, η isoentropic efficiency, $\dot{V}_{IN}$ turbine inlet volumetric flow

	U	S	Cost
	W/m²K	*m²*	*10³€*
Condenser	722	1515	186
Evaporator	1894	156	300
Preheater	457	257	200
	η	$\dot{V}_{IN}$	**Cost**
		m³/s	*10³€*
Turbine	0.866	1.12	250
	Cost (10⁶€)		
Components cost	0.936		
Air cooler	0.319		
Estimated plant cost (with B.O.P.)	1.643		

As an overall comparison it can be stated that Solkatherm allows the same performance of isopentane, but with a higher (+11%) plant cost

6. CONCLUSIONS

The calculations performed have shown that the adoption of Solkatherm, which is a non-flammable and environmentally benign fluid, as a ORC working fluid for geothermal applications, allows the same performance of isopentane, even if its transport properties and saturation curve are different from transport properties of isopentane. As a consequence of the difference in the transport properties a larger sizing of the components and an about 10-15 % higher plant cost is to be accounted for. Note should be taken that the cost of the working fluid has not been included in the preliminary calculation.

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