Proceedings World Geothermal Congress 2010
Bali, Indonesia, 25-29 April 2010

Integration of Geothermal Liquid Dominated Sources and Waste Heat Sources for Electricity Production

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Keywords: ORC, Organic Rankine Cycles, hybrid plant.

ABSTRACT

Liquid dominated geothermal sources, which are broadly distributed and characterized by rather low temperature, can be profitably integrated with a heat source characterized by a higher temperature in order to generate power by means of a thermodynamic cycle working between both hot sources and the ambient temperature of the surroundings. A number of options are available for the higher temperature heat source: biomass plant combustion gas, landfill gas and urban waste incineration combustion gas are just a few examples. In all cases a high performance is obtained by properly joining a topping regenerative ORC cycle, fed by the higher temperature source, with a bottoming saturated ORC cycle, in such a way that the heat required for the evaporation of the bottoming cycle working fluid comes from the condensation of the topping cycle, and the heat required for the liquid preheat comes from the geothermal source. If both cycles are properly optimized and matched, excellent conversion efficiency can be obtained.

1. INTRODUCTION

Liquid dominated geothermal sources are broadly distributed all over the world and characterized by rather low temperature. In this paper particular reference will be made to a situation in Germany, where three main Hot Water Aquifers exist (Schellschmidt et al. (2007)): the Northern German Basin, the Upper Rhine Graben and the Southern Germany Molasse Basin. In almost all cases maximum hot water temperature is in the temperature range 130-160 °C, being somewhat lower in the Molasse Basin (about 130°C).

Several examples exist in Europe of geothermal energy exploitation for both direct uses and electric power production from the same well (well known is Altheim, in Austria): in this case the initial exploitation of geothermal fluid for district heating was followed by electric energy generation, so as to boost plant performance and economics. Plant performance and economics may be brought to a better result by coupling the geothermal source to a second source, which could also be renewable, in order to obtain a hybrid plant generating both electric energy and heat. Note that, if the second source is also renewable or associated with a renewable source, higher electric energy selling prices could be applicable and plant economics could be greatly enhanced.

In this paper, the geothermal source is profitably integrated with a heat source characterized by a higher temperature in order to generate power by means of a thermodynamic cycle working between both hot sources and the ambient temperature. A number of options are available for the high temperature heat source: combustion gases obtained by burning biomass in a furnace or urban waste in an incinerator are just a few examples. ORC technology, which is commonly adopted both in geothermal liquid dominated sources and biomass or small waste incineration plants can be applied to the whole integrated hybrid plant.

2. PLANT DESCRIPTION

The hybrid plant is fed both by the geothermal source and the residual fuel (waste, biomass etc.) and generates only electric power in summer while it generates both electric power and heat for a district heating network in winter. A sketch of the adopted plant scheme is drawn in figure 1. In summer all the geothermal fluid is sent to the ORC power plant; in winter and mid season the request of the district heating network is considered first, and the geothermal fluid is split in two flows so as to provide the requested thermal power for the district heating network and to send the remaining fluid to the ORC power unit.

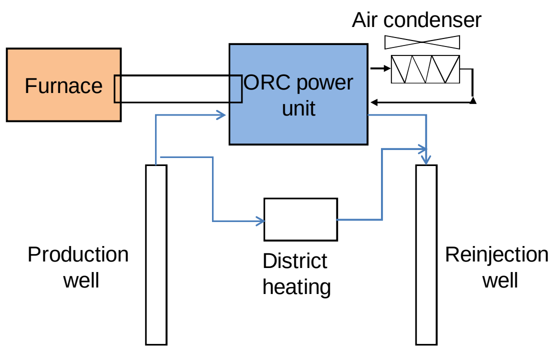

Figure 1: Hybrid plant scheme

The high temperature heat is introduced in the hybrid power plant by means of a combustion process: biomass or urban waste is burned in a combustor made according to the well established techniques in use also for hot water, biomass fed, boilers. Biomass/waste combustors are complemented with a set of accessories (filters, controls, automatic ash disposal and fuel feed mechanism etc.) so that overall the high temperature heat source is characterized by safe, reliable, clean and efficient operation and therefore the entire hybrid power plant is characterized by clean and reliable operation.

Hot thermal oil is used as heat transfer medium between the combustor and the ORC plant section according to a well established criterion, giving a number of advantages, including low pressure in boiler, large inertia and insensitivity to load changes, simple and safe control and operation, easy maintenance and heat exchanger cleaning; moreover the utilization of a thermal oil boiler also allows operation without the licensed operator required for steam systems in many European countries.

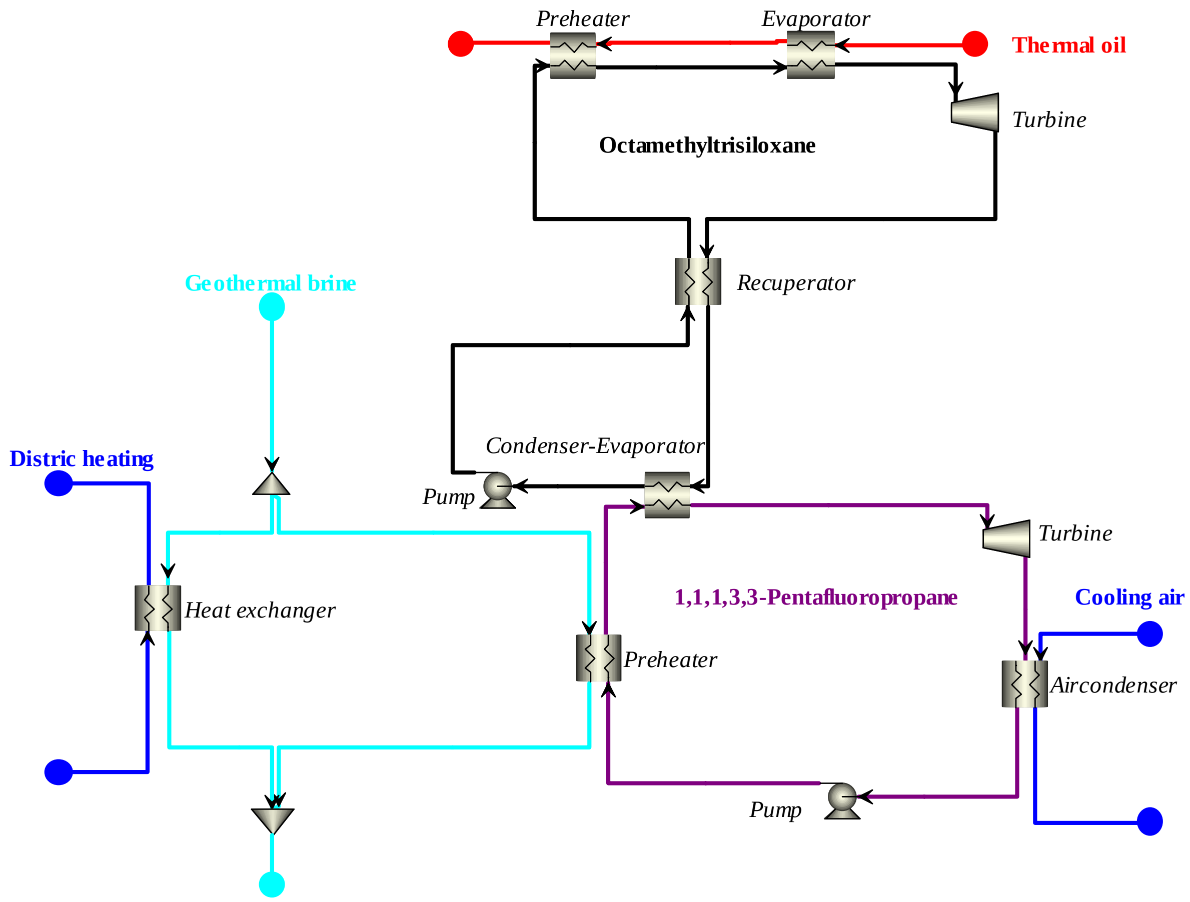

Figure 2: Plant scheme as implemented for calculation.

As the exhaust of the municipal waste or biomass plant may contain several corrosive components, hot corrosion is a potential danger for the boiler components which must be avoided by adopting a conservative temperature range for the thermal oil loop. A limited maximum temperature (about 300°C) in the heat transfer loop also ensures a long life of the oil and intrinsically protects the ORC working fluid from over-temperature.

In this paper a temperature range of 220-310 °C for the thermal oil loop is selected; these values could be representative of either a small urban waste incineration plant or a biomass plant.

From a thermodynamic point of view, the ORC plant operates by means of a thermodynamic cycle working between two variable temperature heat sources, the thermal oil loop and the geothermal fluid, both charged with heat introduction, and the ambient temperature surroundings, charged with heat rejection.

In order to achieve a high thermodynamic performance, a cascaded cycle is adopted in the ORC plant section: the high temperature, regenerative top cycle is fed by the thermal oil, and the low temperature, bottom cycle is fed by the geothermal source. Working fluids selected for the present simulation are, respectively, MDM (octamethyltrisiloxane) for the top cycle and HCF-245fa (1,1,1,3,3-pentafluoropropane) for the bottom cycle.

A more detailed plant scheme, as implemented for the calculation, is shown in fig. 2.

3. PERFORMANCE EVALUATION

The thermodynamic analysis of the hybrid plant was performed by means of process simulator developed for calculations of complex power plants. The thermodynamic properties of the ORC working fluid were calculated by means of a modified Peng-Robinson equation.

3.1 Basic Assumptions

In the calculation a fixed size a high temperature section was adopted, fed by the thermal oil, and complemented by a low temperature section, fed by the geothermal fluid, with a size variable according to the geothermal fluid inlet temperature. On design condition is assumed in summer, with all electric operation and with all the geothermal fluid flow fed to the ORC plant: the geothermal mass flow divided according to its inlet temperature and assumed discharge temperature, so as to optimize the heat transfer diagram and give all the required heat to the bottoming cycle working fluid in order to satisfy preheat design conditions. The selection of the geothermal fluid discharge temperature is of particular concern: it may be dictated by scaling requirements or sustainability of resource exploitation or both; in the present paper it is assumed that no scaling constraints exist, and the value selected is therefore meaningful as far as sustainability is concerned. In winter and mid season operation the plant generates both electric energy and heat for the district heating network; in all operating conditions (summer, winter and mid season) the geothermal fluid flow is assumed constant.

The main input data considered for calculations are reported in table 1 and 2.

Table 1: Heat sources and district heating network basic input data

Thermal oil temperature range	310-220 °C
Thermal oil mass flow	75 kg/s
Geothermal fluid inlet temperature	parameter
Geothermal fluid discharge temperature, on design condition	65 °C
Geothermal fluid salt content	1 g/l
Condenser cooling medium	Air
Temperature increment of condenser cooling medium	10 °C
Supply and return district heating temperatures	80-60 °C
Winter peak district heating thermal power	8 MW

Table 2: ORC cycle basic assumptions

Top cycle turbine on-design isoentropic efficiency	0.80
Bottom cycle turbine on-design isoentropic efficiency	0.85
Pumps hydraulic efficiency	0.70
Electric generator efficiency	0.96
Pump motor efficiency	0.95
Air cooler consumption, percentage of condensation heat, on-design operation	1%
Top cycle working fluid	MDM
Bottom cycle working fluid	HFC-245fa

All power plant components are dimensioned for the on-design constraint of all electric operation. During all other operations, when the geothermal fluid flow is split so as to feed the district heating network as well, off-design conditions of the various components are estimated; turbine efficiency variation is accounted for assuming variable inlet nozzles and following the correlations of (Aungier, 2006)

3.2 Calculations

Calculations were first performed with respect to a reference case, with a geothermal fluid inlet temperature of 130°C, and later by considering a parametric analysis with using the geothermal fluid inlet temperature as parameter. For each of the geothermal fluid inlet temperatures considered, the summer, winter and mid season operation was calculated. For every plant operating condition the net plant electric power, First Law thermal efficiency, and Second Law efficiency were evaluated.

Net plant electric power is calculated as:

$$P_{net} = P_{MDM} + P_{R245\,fa} - P_{fans} - P_{DHP} \qquad (1)$$

where P_{net}, P_{MDM}, $P_{R245\,fa}$, $P_{aircond}$, P_{DHP} are respectively the total plant net electric power, the net electric power of the MDM cycle, the net electric power of the R245fa cycle, the total electric consumption of the air condenser fans and the consumption of the geothermal fluid pump.

First Law efficiency is defined as follows:

$$\eta_I = \frac{P_{el} + \dot{Q}}{\dot{m}_{oil} \cdot \Delta h_{oil} + \dot{m}_{geo} \cdot \Delta h_{geo}} \qquad (2)$$

where P_{el}, Q, m_{oil}, Δh_{oil}, m_{geo}, Δh_{geo} are respectively, the net plant electric power produced, the district heating thermal power, the thermal oil mass flow, the thermal oil specific enthalpy difference, the geothermal fluid mass flow and the geothermal fluid specific enthalpy difference.

Following Di Pippo (2004), a functional exergy efficiency, defined as the ratio of the exergy associated with the desired energy output to the exergy associated with the energy expended to achieve the desired output, is adopted to evaluate the Second Law efficiency. Therefore

$$\eta_{II} = \frac{P_{el} + \dot{Q}\left(1 - \frac{T_0}{T_Q}\right)}{\dot{m}_{oil} \cdot \Delta e_{oil} + \dot{m}_{geo} \cdot \Delta e_{geo}} \qquad (3)$$

where P_{el}, T_0, T_Q, Q, m_{oil}, Δh_{oil}, m_{geo}, Δh_{geo} are respectively, the net plant electric power produced, the district heating thermal power, the ambient temperature, the logarithmic mean temperature between the supply and return temperatures of the district heating network, the thermal oil mass flow, the thermal oil specific exergy difference, the geothermal fluid mass flow and the geothermal fluid specific exergy difference.

<u>3.2.1 Reference Case</u>

Reference case was calculated with respect to heat sources regarded as representative for the Southern German Molasse Basin area, i.e. with a geothermal inlet fluid temperature of 130°C; with an ambient air temperature equal to 18 °C for summer operation, equal to -1 °C for winter operation, equal to 9.6 °C for mid-season operation, which all correspond to the seasonal mean values for the Munich area. Calculation results are presented in table 3.

Actual performance with respect to heat source exploitation is represented by first law efficiency, while second law efficiency represents the plant performance with respect to an ideal process and points out possible weak points which could be improved with plant modification. It is therefore interesting to look at figure 3 and table 4, where temperature vs. power in the various cycle components and second law analysis are shown.

All the heat transfer processes are shown in fig. 3: heat required for the preheating of the top cycle working fluid is introduced first by the hot turbine exhaust vapor (regenerative process) and later on by the thermal oil, which also accomplishes the fluid evaporation; heat required for the preheating of the bottom cycle fluid is introduced by the geothermal water, while heat required for the evaporation comes from the top cycle working fluid which condenses. Heat rejected to the ambient is given to ambient air. As a matter of fact, all the heat transfer processes are reasonably well matched (except for the MDM evaporation and, on a less extent, R245fa desuperheating, which both involve a low fraction of heat exchanged).

Table 3: Calculation results for reference case

	On design	Winter	Mid-season
T_0	18.0	-1.0	9.6
Oil thermal power, MW	16.4	16.4	16.4
Geothermal fluid thermal power, MW	14.0	17.3	15.9
Geothermal fluid mass flow, kg/s	51.1	51.1	51.1
Geothermal fluid discharge temperature , °C	65	49.3	56.5
ORC_{MDM} net power, kW	2552	2657	2402
ORC_{R245fa} net power, kW	3621	3312	3655
Air cooler consumption, kW	240	195	220
Geothermal fluid pump consumption, kW	132	132	132
Plant net power, kW	5800	5642	5705
DH thermal power, MW	0	8	4
η_I	0.195	0.404	0.300
η_{II}	0.550	0.593	0.564

The advantage of this positive condition is clearly noticeable in table 4, where Second Law efficiency is calculated from the reversible ideal efficiency by subtracting all components percentage exergy losses according to:

$$\eta_{II} = 100 - \frac{T_0 \cdot \sum \Delta \dot{S}}{\dot{m}_{oil} \cdot \Delta e_{oil} + \dot{m}_{geo} \cdot \Delta e_{geo}} \quad (4)$$

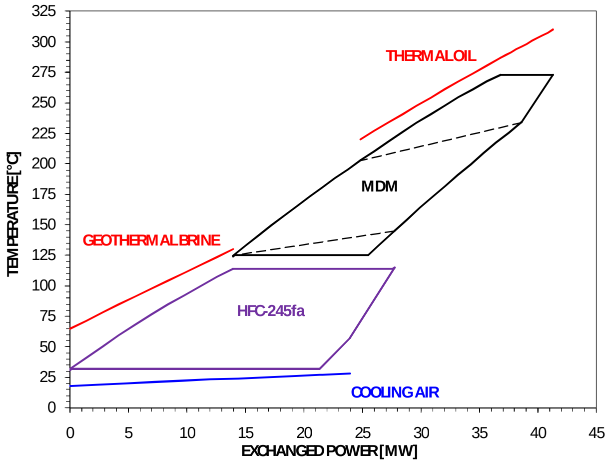

Figure 3: Temperature vs. power in the various cycle components for reference case (130°C), all electric, summer operation

Table 4: Second Law analysis for on design operation

Component	%
MDM preheater+evaporator	2,69
MDM recuperator	3,79
MDM cond/ R245fa evap	3,09
R245fa preheater	6,97
R245fa condenser	7,50
Cooling air discharge	3,84
MDM turbine	3,87
MDM pump	0,33
R245fa turbine	6,06
R245fa pump	0,53
ORC mec., el. loss, aux cons.	5,03
Downhole pump	1,26
Total work obtained	55,03

All the loss terms related to heat transfer introduction are in fact quite low: the larger term is related to the heat provided by the geothermal fluid, which is strongly dependent on the geothermal fluid discharge temperature: if this can be lowered, the loss term of the R245fa preheater becomes smaller, and even better global performance can obtained.

It is to be noted that, if both heat sources were used separately, with air condensation at the same ambient temperature, much lower performance would be obtained: a separate geothermal ORC cycle would produce 987 kW, and a separate ORC cycle fed by the same thermal oil would produce 3508 kW, thus a total electric power of 4363 kW when also the geothermal pump fluid consumption is detracted, i.e. much lower than that of the hybrid plant net power (5800 kW). Furthermore power plant cost would be much higher, as no integration between the plant components would be possible.

In off design operation the position of the ORC cycles between the thermal sources is changed but still very good performance can be obtained.

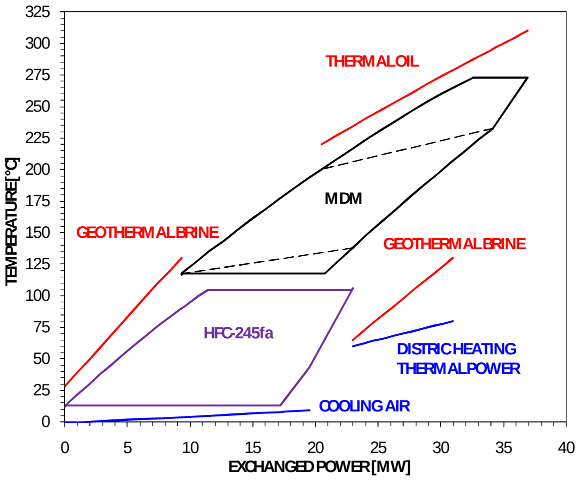

Figure 4: Temperature vs. power in the various cycle components for reference case (130°C), winter operation

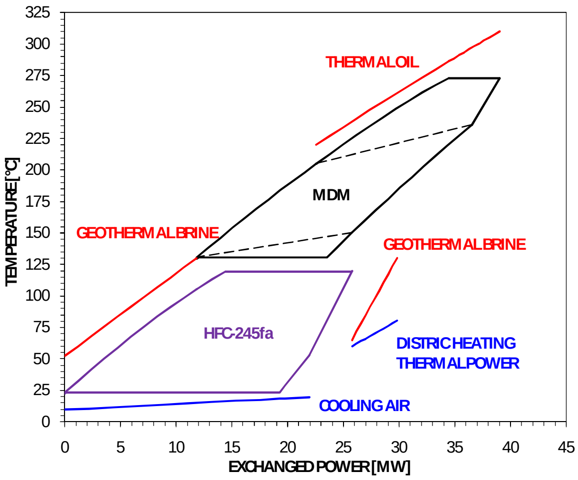

Figure 5: Temperature vs. power in the various cycle components for reference case (130°C), mid season operation

For simplicity, during off design operation, air cooler consumption is maintained constant, i.e. 1% of the thermal power exchanged but it is reasonable to think that consumption could be lower, because the required cooling air mass flow gets lower.

During mid season and winter, the ambient temperature decreases: this means that, the condensing temperaure of the bottom cycle gets lower, and more heat is required for the working fluid preheat; at the same time, geothermal fluid is required also for suppling the district heating network: therefore more heat must be extracted from the geothermal reservoir. If the brine flow is considered to be constant, the discharge temperature will be lower than during on design operation. Sustainable exploitation analysis must therefore be performed considering the variation of the discharge temperature all over the year.

Plant net power is maximum in summer, providing all electric operation, and is equal to 5800 kW; however, during winter operation, even if slightly more than half of the geothermal fluid flow is used for suppling the district heating network, the net power is only somewhat reduced, (5642 kW) because the low ambient temperature gives a substantial contribution in attaining better performance. An intermediate situation is found during mid season operation. (5705 kW).

The thermal power produced is relevant in respect to the electric power produced (8000 kW versus 5642 kW) during winter operation, and this brings a noticeable increase of the I and II law efficiencies, which go respectively from 0.195 to 0.404 and from 0.550 to 0.593; in mid season operation more electric than thermal power is produced (5705 kW versus 4000 kW) and, also, the thermodynamic value of the produced heat is not so high as in winter, because the ambient temperature is higher (9.6 versus -1 °C), and therefore the increase in efficiency is greater for first law efficiency (which attains 0.300) than second law efficiency (which attains 0.564).

3.2.2 Parametric Analysis

Additional calculations were performed in order to investigate the plant performance with the same high temperature plant section (same heat introduction process) and hotter or colder than reference case geothermal fluid.

Table 5: Calculation results for geothermal fluid inlet temperature 110 °C

	On design	Winter	Mid-season
T_0	18.0	-1.0	9.6
Oil thermal power, MW	16.4	16.4	16.4
Geothermal fluid thermal power, MW	8.3	8.6	9.6
Geothermal fluid mass flow, kg/s	44.0	44.0	44.0
Geothermal fluid discharge temperature , °C	65	63.81	58.55
ORC_{total} net power, kW	5179	4645	4862
Geothermal fluid pump consumption, kW	88.9	88.9	88.9
Plant net power, kW	5090	4556	4773
DH thermal power, MW	0	8	4
η_I	0.206	0.502	0.337
η_{II}	0.558	0.610	0.561

Two different sets of calculation were performed: (i) with a geothermal fluid inlet temperature of 110 °C (table 5) and 150 °C (table 6). Results for net plant power and efficiencies are then summarized in figures 8 and 9.

Table 6: Calculation results for geothermal fluid inlet temperature 150 °C

	On design	Winter	Mid-season
T_0	18.0	-1.0	9.6
Oil thermal power, MW	16.4	16.4	16.4
Geothermal fluid thermal power, MW	25.7	30.7	25.6
Geothermal fluid mass flow, kg/s	71.4	71.4	71.4
Geothermal fluid discharge temperature , °C	65.00	48.21	65.00
ORC_{total} net power, kW	7606	7132	7239
Geothermal fluid pump consumption, kW	234.5	234.5	234.5
Plant net power, kW	7371.5	6897.5	7004.5
DH thermal power, MW	0	8	4
η_I	0.175	0.316	0.262
η_{II}	0.545	0.528	0.540

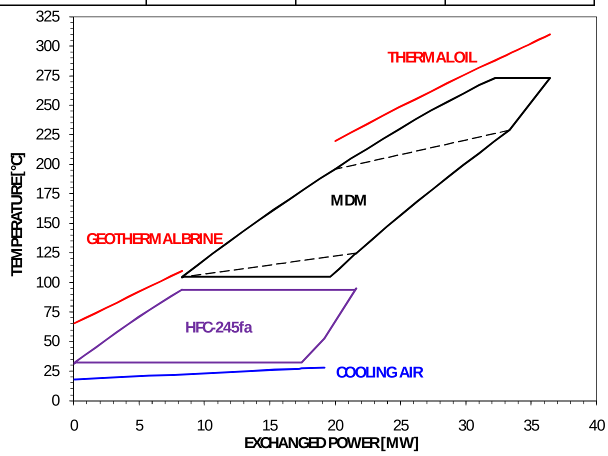

Figure 6: Temperature vs. power in the various cycle components for 110°C geothermal brine inlet temperature, on design condition

As the geothermal fluid inlet temperature is varied, the position of the cycles between the heat sources is varied, and the geothermal fluid mass flow needed to give heat to the bottom cycle working fluid to accomplish preheat varies as well; as the mass flow increases with temperature increase, the thermal power introduced by the geothermal fluid increases with temperature. In summer, with all electric operation, the ratio between geothermal fluid thermal power and oil thermal power is as follows: 0.50 for 110° C; 0.85 for 130°C; 1.56 for 150°C.

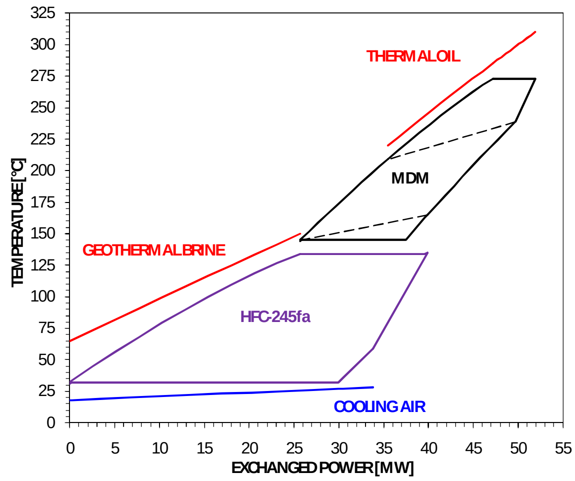

Figure 7: Temperature vs. power in the various cycle components for 150°C geothermal brine inlet temperature, on design condition

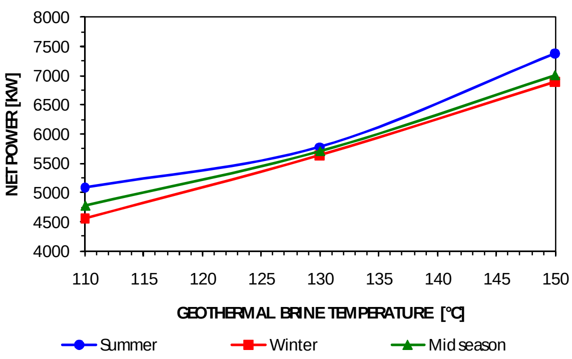

Figure 8: Net electric plant power versus geothermal fluid inlet temperature for different operating conditions

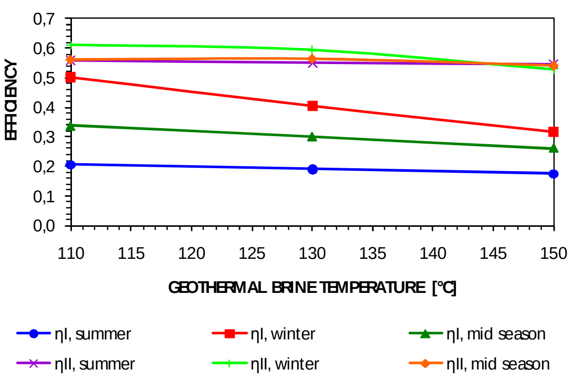

Figure 9: First Law and Second Law efficiency versus geothermal fluid inlet temperature for different operating conditions

The plant net power increases with geothermal fluid inlet temperature: this is clearly due to the increased thermal power introduced by the geothermal fluid. Differences between on design and off design operation are always less than 10% and is minimum for the 130°C reference case.

By considering the results presented for the efficiencies in fig. 7, it can be inferred that:

(i) first law, summer, all electric efficiency gets somewhat lower with increasing temperature, and this can be explained considering that, from one side, the low temperature source temperature gets higher, but, on the other side, the ratio between the introduced oil, high temperature thermal power and geothermal fluid, low temperature thermal power, becomes smaller with increasing temperature, thus providing the curve depicted in figure

(ii) first law, mid season and winter coupled electric and thermal generation efficiency is always higher than all electric, but the difference diminishes with increasing temperature because the ratio between thermal power and electric power produced get smaller

(iii) second law efficiency is highest in winter operation, and variations both with operating conditions and geothermal fluid inlet temperature are maintained in a narrow range between 0.54 and 0.61

4. CONCLUSIONS

Exploitation of liquid dominated geothermal sources by means of a hybrid plant was investigated, where the geothermal source is coupled to a higher temperature source which could be represented by biomass plant exhausts, landfill gas and urban waste incineration exhausts etc.

Performance analysis has shown that performance attainable with the hybrid plant is much higher than with separate plants; second law efficiencies, which depend on geothermal fluid inlet temperature and operating condition, are always noteworthy and comprised in the range 0.54-0.61.

Geothermal fluid discharge temperature, which varies according to operating condition, is an important parameter to get the highest performance from the hybrid plant; it must therefore be carefully selected, according to scaling and sustainable exploitation of geothermal resource.

Plant maximum net electric power is found with high geothermal fluid inlet temperature, but highest first and second law efficiencies are found with low geothermal fluid inlet temperature.

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