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The Geothermal Rankine Steam Cycle Compared to the Geothermal Flash Cycle

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ABSTRACT

This paper compares studies of the common geothermal flash steam cycle and the Rankine steam-cycle powered by high-temperature geothermal two-phase fluid, with the aim of generating electricity. The concept of the geothermal Rankine steam cycle is based on the utilization of high-temperature geothermal two-phase fluid at the Nesjavellir high-temperature geothermal area. Small shell-and-tube heat exchangers have been in periodical operation during the past eight years, generating hot water by the geothermal two-phase fluid for local district heating utility.

Despite considerable content of amorphous silica in the geothermal fluid, no extensive scaling has been detected nor have the heat exchangers needed to be cleaned. It is therefore assumed feasible to generate steam, as well as the heating of water, through the use of geothermal two-phase fluid in heat exchangers at Nesjavellir. It is also considered feasible to generate steam in various geothermal fields with similar chemical composition as the fluid at Nesjavellir.

Technical and economical comparison of the two cycles indicates that if the heat extraction of the geothermal two-phase fluid is feasible, the geothermal Rankine steam cycle could be considered as an alternative to the geothermal flash cycle. If the geothermal fluid has a high content of non-condensable gasses (NCGs), the geothermal Rankine steam cycle becomes even more advantageous in comparison.

The comparison takes notice of the geothermal Rankine steam cycle's benefits of a clean steam operation and the disadvantage of increased costs due to increased requirements of heat exchangers.

1. INTRODUCTION

A comparison study will be made between the common geothermal flash steam cycle and the Rankine steam cycle powered by geothermal two-phase fluid (called the geothermal Rankine steam cycle in the paper), with the aim of electricity generation.

The main difference between the geothermal Rankine steam cycles and the common Rankine steam cycles powered by fossil fuel is the rate and the size of the boiling components. The boiling components are also the most critical factors in the geothermal Rankine steam cycle for following reasons:

- Technically, due to possible scaling of the boiling component where the geothermal fluid passes.
- Economically, due to the large heat-exchange surface area requirements.

The technical feasibility has been verified by small shell-and-tube exchangers at the Nesjavellir high-temperature geothermal field in Iceland. These heat exchangers have been in periodical operation for eight years, generating hot water by heat extraction of the geothermal two-phase fluid. This operation results in no extensive scaling or need for cleaning. It is therefore assumed feasible to generate steam as well as heated water by the geothermal two-phase fluid in heat exchangers at Nesjavellir and at geothermal fields with similar chemical composition of the fluid compared to Nesjavellir.

To achieve the best possible economical performance of the geothermal Rankine steam cycle, the aim of the construction is a minimum required heat-exchange surface area. This may be achieved with a sophisticated construction, such as forced circulation of the fluids and wetted condition of the generating steam from the outlet of the boiler.

Alternative cycles, such as the organic Rankine cycle (ORC), combined steam/ORC cycle and the Kalina cycle, will be considered. Finally, the geothermal Rankine steam cycle is compared to the geothermal flash steam cycle with typical working conditions in geothermal application. In the comparison, a rough estimation is accomplished where investments and operational cost is taken into account.

2. THE CONCEPT OF THE GEOTHERMAL RANKINE STEAM CYCLE

In this section a geothermal two-phase-flow heat-exchange process at Nesjavellir is introduced. Then the concept of a boiling process and heat exchangers based on the two-phase-flow heat exchanger process at Nesjavellir is described. Finally, alternative cycles are considered.

2.1 Geothermal two-phase-flow heat-exchange process at Nesjavellir

At Nesjavellir a small shell-and-tube heat exchanger has been periodically in operation for eight years, producing hot water for a district heating utility. The heated water passes along the shell sides. The geothermal two-phase fluid passes along the tube sides. It consists of a steam-phase with non-condensable gases and a water-phase with a dissolved solid containing a high proportion of silica. Amorphous silica saturation is reached in the brine at Nesjavellir at 165-180°C. Despite the considerable amorphous silica-saturated condition of the geothermal fluid in the heat exchangers, no extensive scaling has been found nor is any requirement for cleaning required. The total period of operation of the heat exchangers is estimated to amount to up to 25,000 hours.

It is therefore assumed feasible to generate steam as well as heated water by the geothermal two-phase fluid in heat exchangers at Nesjavellir and at geothermal fields with similar chemical composition as the fluid at Nesjavellir. The typical chemical composition of the geothermal fluid at Nesjavellir is given in Table 1. A diagram of the process is shown in Figure 1 and a flow diagram in shown in Figure 2.

Table 1. Chemical compositions of the fluid at Nesjavellir

STEAM	PPM	BRINE	PPM
CO_2	2000 - 2500	Ph/°C	7.5 – 8.0/25
H_2S	500 - 1500	SiO_2	700 - 1000
H_2	70 - 170	Na	80 - 1000
CH4	0 - 5	K	80 - 130
N_2	50 - 120	Ca	0,3 - 1,0
		Mg	0 - 0.1
		SO_4	10 - 50
		Cl	2 - 100
		H_2S	50 - 100
		CO_2	20 - 40

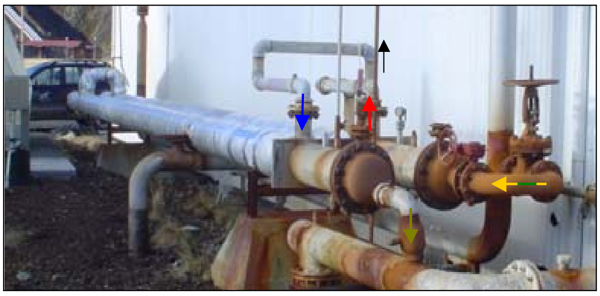

Figure 1. Geothermal two-phase flow heat exchangers at Nesjavellir.

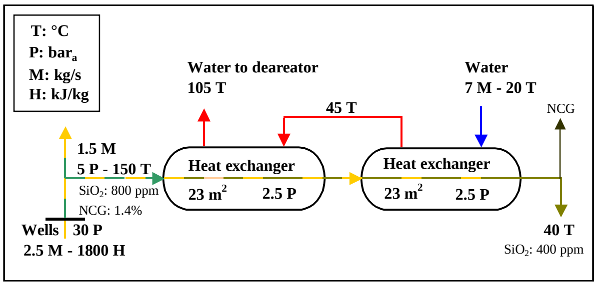

Figure 2. The Geothermal two-phase flow heat exchange process – Flow diagram.

2.2 The concept of the boiling process.

The main difference between the geothermal Rankine steam cycle and the flash steam cycle is the arrangement of the geothermal fluid component parts where heat exchangers are used instead of separators. Other component parts may be considered as similar. In the Rankine steam cycle, the boiling-component heat-exchanger surface area is considered as a critical factor in the investment cost. The aim of the construction must therefore be a minimum required heat-exchanger area and the most economical selection of sizes and materials. This could be achieved with following arrangement:

- Condensing and cooling of the geothermal two-phase fluid at high velocity. This results in an effective heat-transfer performance.
- Heating and boiling of the generating steam by forced circulation and a wetted steam condition at the outlet of the boilers. With a wetted steam flow, a much better heat transfer performance is achieved compared to saturated or superheated steam flow.

A feasible boiling performance is shown in Figure 3. The boilers are preferred as a kettle-type reboiler, double-pass, either with floating head according to Figure 4 or with a U-tube bundles according to Figure 5.

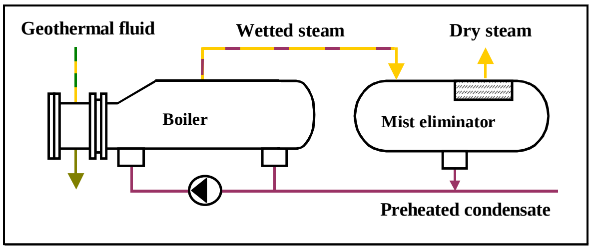

Figure 3. Feasible boiling performance.

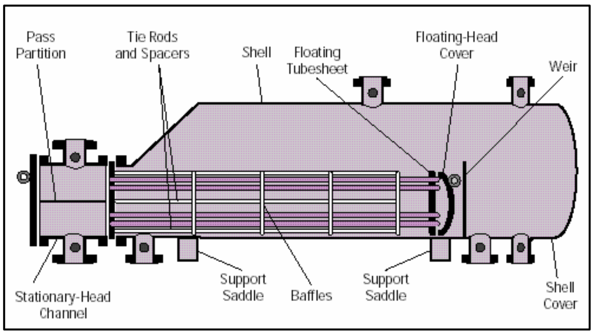

Figure 4. Feasible floating head tube boiler.

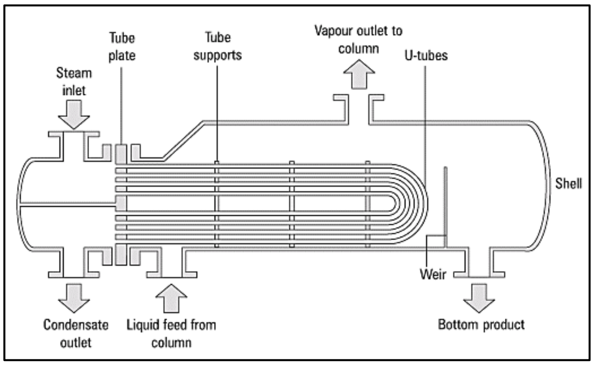

Figure 5. Feasible U-tube boiler.

Boilers of the U-tube type are considered as more economical but boilers of the floating-head type are considered as easier to clean on the tube side compared to U-tube boilers. The tube element of these boilers can be replaced with spare tube elements. The advantage is minimum downtime in case of failure.

The selection of boiler types and materials depends on investment cost, the scaling rate of the geothermal fluid and possible cleaning methods. To reduce cost, large heat-exchange units are preferred. Whether the choice is a pair of boiler and preheater connected serially, or an additional pair parallel, depends on what is considered most advantageous. Carbon steel is considered as the most economical material selection for the heat exchangers. The working steam on the shell side should not affect carbon steel, but the geothermal steam condensing in the tubes could affect carbon steel. Preferably, any type of stainless steel has to be selected as tube material.

In the paper "The implementation of a steam transformer system" there is reported a steam-to-steam U-tube boiler (3 bar_a-to-1.4 bar_a) with an extremely good heat transfer performance (OHTC 3.7 kW/m^2 °C). The paper describes a boiler with a 600-m^2 heat-exchange surface area and a steam-generating capacity of 13.9 kg/sec.

The paper "Industrial use of geothermal energy at the Tasman Pulp & Paper Co. Ltd at Kawery" is a description of a geothermal steam-to-steam floating-head boiler (7 bar_a-to-3.5 bar_a). The paper describes a boiler with a 620-m^2 heat-exchange surface area and steam-generating capacity of 8.3 kg/sec.

These papers indicate steam-to-steam systems with a variety in heat transfer efficiency. This may cause a difference in condition and velocity of the fluid, etc. The emphasis is made that with a sophisticated construction the required heat-exchanger area can be kept at a minimum.

2.3 Alternative cycles.

The main scope of this paper is a comparison study of the geothermal flash steam cycle and the geothermal Rankine steam cycle at the higher temperature rating. Another feasible cycles such as organic Rankine cycle (ORC), Kalina cycle and combined steam/ORC could also be considered. In brief, the ORC and the Kalina cycle are not in application at higher temperature rating and therefore not considered actual to compare with. The combined steam/ORC cycle is in several geothermal applications at higher temperature rating and therefore considered actual to compare with. Because the combined steam/ORC are already in use, it's supposed that comparison study of the cycle and the common flash steam cycle have already been accomplished. Those who want to compare the cycles this paper is focused on, with the combined steam/ORC are advised to search for relevant papers.

3. COMPARISON BETWEEN THE GEOTHERMAL RANKINE STEAM CYCLE AND THE GEO-THERMAL FLASH CYCLE

In this section, a preferred flow diagram of the geothermal Rankine steam cycle is presented. For comparison, a corresponding geothermal flash cycle is represented. These processes are compared both technically and economically, with a rough estimation of investment and production cost.

3.1 The geothermal flash cycle - Technical concept.

A preferred flow diagram of the compared geothermal flash cycle is shown in Figure 6. Generation of steam by flashing 150 kg/s of geothermal fluid with enthalpies of 1520 kJ/kg is 60 kg/sec. at 7 bar_a.

Overall turbine efficiency (total of turbine, generator and diverse), based on recent geothermal turbines manufacturers references for 30 MW_e geothermal steam turbines, is estimated to be 80% (List of geothermal power plant, Mitsubishi heavy industry, LTD, Japan 2000). Condensate pressure is selected to 0.1 $bar_{a.}$ With the presence of geothermal gases as 1% of the total flow, it is hardly profitable to reach a much lower condensate pressure.

With these presuppositions, the gross power output is estimated to be 30.6 MW_e and the net power output 28.6 MW_e. The NCGs are normally removed with steam ejectors, vacuum pumps or a hybrid solution of these methods. This energy absorption is estimated to be 1 MW_e, based on actual examples (List of geothermal power plant, Mitsubishi heavy industry, LTD, Japan 2000).

3.2 The geothermal Rankine steam cycle - Technical concept.

A preferred flow diagram is shown in Figure 7. The well's fluid, flow and condition, is selected the same as for the geothermal Rankine steam cycle in Figure 6. The pressure at the steam-gathering system is selected at the common rate of 7 $bar_{a,}$ in geothermal with a corresponding generating steam pressure of 3.5 bar_a. These parameters are with reference to an actual example at the Tasman Pulp Kawerau geothermal field (see section 2.2).

With the flow condition of the geothermal well fluid according to Figure 7 and the boiling process described in section 2.2 (600-m^2 boiler, generating 13.9 kg/sec. of steam at 1.4 bar_a), the required boiling heat-exchange surface area is conservative estimated as 3,000 m^2, generating a 58 kg/s of steam at 3.5 bar_a. The required preheating heat-exchange-surface area, based on empirical heat-transfer parameters of water to brine in the geothermal, is estimated as 1,500m^2 (actual example for water to brine at Nesjavellir power plant).
Overall turbine efficiency is normally slightly advantageous for clean steam turbines compared to geothermal turbines. Based on 80 % overall turbine efficiency for the compared geothermal turbine, the overall turbine efficiency for the Rankine steam turbine is estimated as 83%. Condensate pressure is selected as 0.05 bar_a. The absence of geothermal gases results in a better capability of reaching a lower condensate pressure. According to the Siemens steam turbine manufacturer, the optional condensate pressure would be 0.04-0.4 bar_a. With these presuppositions, the gross power output is estimated to be 29.8 MW_e and the net power output 28.3 MW_e.

Another output of the process is an estimated 100 kg/sec. mixture of condensate and brine possible for alternative applications, such as industrial, heat or power production.

It is also possible to use all the mixture of steam and condensate (150 kg/sec.) for preheating. With this alteration, the heat-exchange surface area can be reduced from ca. 1,500 m^2 to ca. 500 m^2 (increased log. mean temperatures).

3.3 The geothermal Rankine steam cycle and the geothermal flash cycle – Rough economical comparison.

A conventional geothermal flash cycle according to Figure 6 and a geothermal Rankine steam cycle according to Figure 7 are compared. To evaluate the investment cost of the geothermal Rankine steam cycle, additional cost is estimated for the boiling components and the cost subtracted for the separators components. Other costs are estimated to match. For example, the investments cost due to NCGs removal are higher for the geothermal flash cycle, and costs due to larger dimension, make-up water, etc. is higher for the geothermal Rankine steam cycle.

Investment cost for a 30 MW_e geothermal flash cycle power plant: The overall investment costs of 30 MW_e geothermal flash cycle power plants are based on average empirical costs. According to a number of sources (based on renewable energy technology fact sheet), this cost is estimated to be USD 40 million (1330 USD/kW installed capacity).

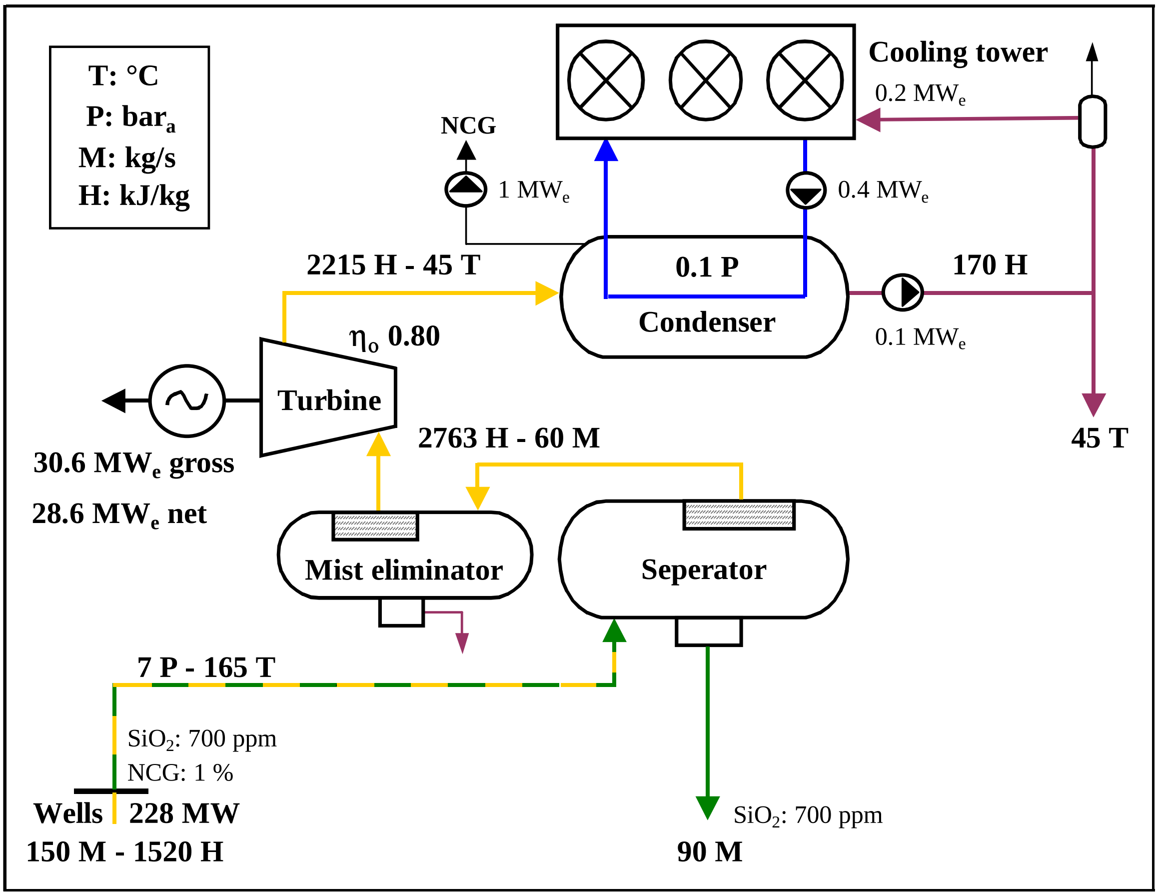

Figure 6. Geothermal flash cycle - Flow diagram.

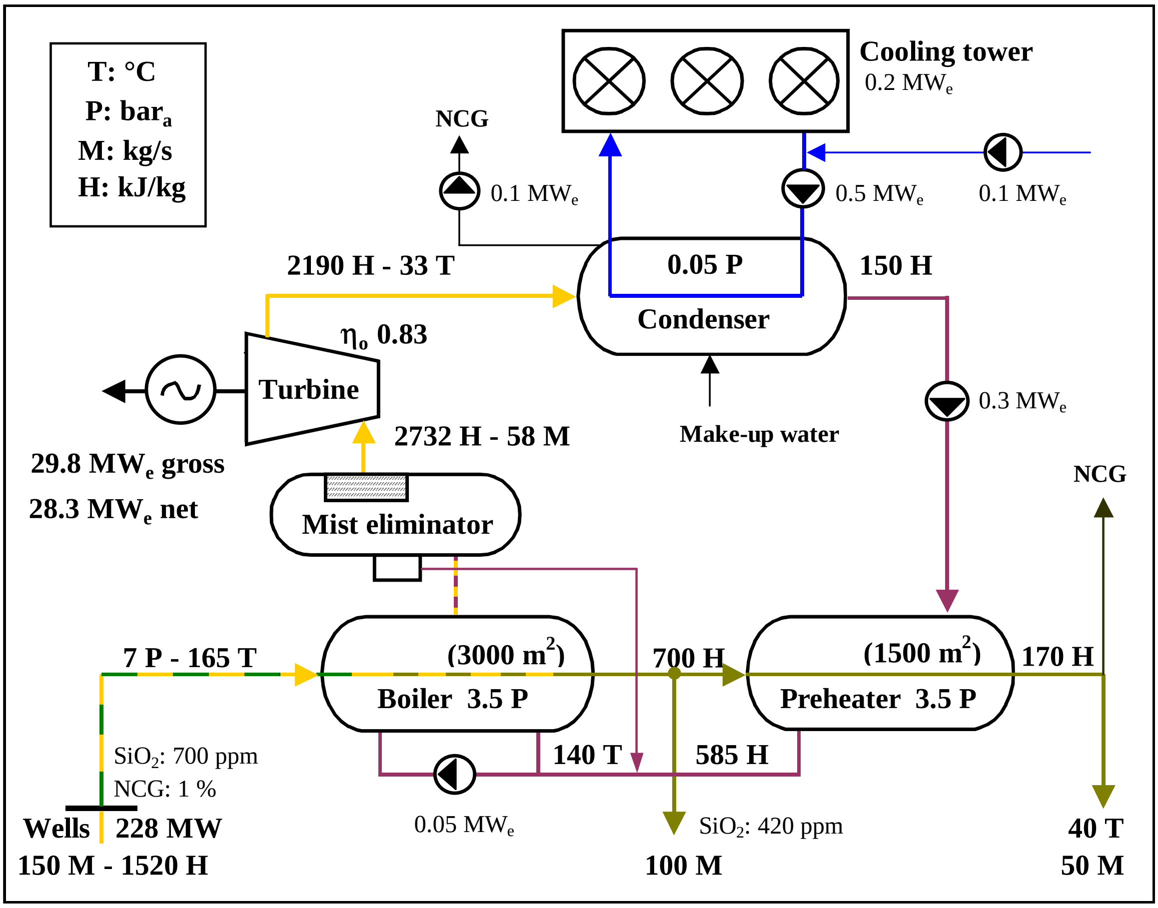

Figure 7. Geothermal Rankine steam cycle - Flow diagram.

Investment cost for separation components for 30 MW_e geothermal Rankine steam cycle power plant is rougly estimated to USD 1 million (actual example at Nesjavellir power plant).

Rough estimated cost of the boiling components (heat exchanger cost calculation):

Boiler (kettle type):	Heat exchange area: 3,000 m^2
	Shell mat.: Carbon steel (CS)
	Tube mat.: Stainless steel (SS)
Alternative:	Tube mat.: Carbon steel (CS)
Calculated cost (CS/SS):	USD 2.0 million
Alt. calculated cost (CS):	USD 0.6 million
Preheater (shell and tube):	Heat exchange area: 1,500 m^2
	Shell mat.: Carbon steel (CS)
	Tube mat.: Stainless steel (SS)
Alternative:	Tube mat.: Carbon steel (CS)
Calculated cost (CS/SS):	USD 1.0 million
Alt. calculated cost (CS):	USD 0.3 million

Based on investment cost of a 30 MW_e geothermal flash cycle power plant of USD 40 million.

Additional costs of boiling components of USD 3 million and subtracted costs of the separation components of USD 1 million.

Total investment cost of a 30 MW_e geothermal Rankine steam cycle power plant is therefore estimated to be USD 42 million.

Rough estimated production cost of the compared cycles (mills/kWh):

	Rankine Steam:	Flash steam:
Net power production Capacity (MW_e):	28.3	28.6
Total investment cost:	42.0	40.0
*Annual cost (25 years at 6% interest):		
Investment cost:	3.28	3.12
(1) Operational cost:	0.70	0.80
Total:	3.98	3.92
Estimated production cost:		
Operational time (h/year):	8.200	8.000
(2) Production (GWh/year):	232	229
Production cost (mills/kWh):	17.2	17.1

(1) Difference in estimated operational costs are explained as follows:

According to an empirical rule-of-thumb, the operational cost of geothermal flash-cycle power plants is determined to be 2% of the investment cost.

Overhauling intervals for geothermal flash cycle turbines are normally 2-3 years.

Overhauling intervals for low-pressure Rankine steam cycle turbines are normally up to 10 years.

According to failure mode analyses of geothermal power plants, 40% of all failures are due to the turbine failure (Hibara Y).

The heat-exchanger operation is supposed to be with a minimum requirement for maintenance and cleaning with reference to the experience of the two-phase-flow heat-exchange process at Nesjavellir. If this presupposition fails, the operation cost of the Rankine steam cycle has to be reviewed.

(2) Extended intervals between overhauls means increased running hours.

4. CONCLUSION

In the paper a feasibility study and a rough cost estimation of the geothermal Rankine steam cycle compared to geothermal flash cycle was made. A rough estimation of the cycles results in similar production costs. It indicates that if it proves feasible to extract heat from geothermal two-phase fluid in a shell-and-tube heat exchanger, a geothermal Rankine steam cycle powered by geothermal two-phase fluid could be considered as an alternative to the geothermal flash cycle.

With the utilization of geothermal fluid carrying a high content of NCGs, the geothermal Rankine steam cycle becomes more favourable compared to the flash steam cycles. For instance, if geothermal fluid is harnessed from deep-seated geothermal recourses, the fluid will most likely carry a high content of corrosive NCGs. It is explained by the presence of NCGs. NCGs reduce the power capability of the flash cycle due to a restriction on reaching a sufficiently low condensate pressure and the energy absorption related to the removal of the NCGs.

The mixture of condensate and geothermal brine is considered as more suitable for alternative utilization, such as industrial or binary, compared to separate geothermal brine due to a lower content of dissolved solids, such as silica, and a corresponding possible scaling affect.

Before this geothermal Rankine steam cycle is considered, the geothermal fluid has to be exploited. This could be accomplished with relatively simple heat exchanger and chemical tests. The design and construction of a geothermal Rankine steam cycle, as described in the paper, is considered feasible if the harnessing of the geothermal fluid is feasible. All the components are considered, as well known and at sufficient availability. For instance, Rankine steam turbines are more readily available than geothermal flash steam turbines, with a wider variety of manufacturers and a corresponding possibility for favourable offers.

To verify the real investment cost of these compared cycles, a commercial proposal has to be made for both cycles with the aim of exploiting a specific geothermal field. The characteristics of the geothermal source are a deciding factor as to which cycle is more advantageous in the comparison.

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