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SIMULATION AND PERFORMANCE ANALYSIS OF THE NEW GEOTHERMAL CO-GENERATION POWER PLANT (OV-5) AT SVARTSENGI

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ABSTRACT

Geothermal power plants, particularly those operating on the flash-steam principle, offer the opportunity to combine electricity generation with direct heat applications. The latter can be accomplished using the thermal energy available in the waste brine and rejected heat from the condenser to heat fresh feed water which can then be distributed to a variety of end users. The modular method is used to simulate and analyze the performance of the new co-generation power plant (OV-5) at Svartsengi that generates electricity via a single-flash process; the turbine's extraction is then used to provide heat for the heat exchangers where fresh water is heated up to 110°C for a district heating system. The static and dynamic behavior of the power plant at different electrical and heat loads can be analyzed by the simulation. Comparison of results with the manufacturer's data indicates that the simulation model can be used to demonstrate different operating conditions of the turbine. The conditions of the turbine extractions are thoroughly studied to determine the range of allowable electrical load that ensures sufficient steam flow from the extractions at different heat loads. In this way it is possible to optimize the operational strategy of the power plant for different electrical and heat loads. The energy balance of this type of geothermal power plant is also presented in this paper.

1. INTRODUCTION

Geothermal power plants, particularly those operating on the flash-steam principle, offer the opportunity to combine electricity generation with direct heat applications. The latter utilization can be accomplished using the thermal energy available in a waste brine and rejected heat in a condenser to heat fresh water, which can then be distributed to a variety of end users. The technical feasibility and design of such co-generation power plants depend on a number of factors, including the reservoir temperature of the geothermal fluid, the type of flash system used in the power plant (single- or double-flash), the distance to end users and the types of applications. The climate, topography and cost of other energy alternatives will also influence the final decision on whether to use geothermal co-generation power plants.

This paper presents the main characteristics of the new co-generation power plant at Svartsengi (OV-5). For this purpose, the OV-5 cycle is simulated, on the basis of the modular method, and its thermodynamic design parameters, such as utilization efficiency and properties of extraction steam, are analysed.

The two main geothermal co-generation power plants currently in existence are at Svartsengi (Bjornsson and Albertsson, 1985) and Nesjavellir (Gunnarsson et al., 1992) in Iceland. The thermal output of these power plants, 125 MW_t and 200 MW_t, respectively, are used for district heating systems. There are also many co-generation power plants in Japan, such as Otake, Mori, and Hatchobaru, but their thermal outputs are less than 4 MW_t and are mainly used for greenhouses, bathing and snow melting (Uchida, 1997).

2. POWER PLANT OV-5

The new power plant at Svartsengi (OV-5) is designed for 30 MW_e electricity generation and 70 MW_t heating output. The district heating part is designed to heat from about 23°C to 90-95°C and de-aerate 240 kg/s of pre-heated fresh water coming from the Ormat turbines. The pumps, final-heaters and coolers pump 70 kg/s of 85°C water to the town of Grindavik and/or 240 kg/s of 110-115°C water to the town of Njardvik (Fig. 1). The maximum pumped in OV-5 to these towns is 240 kg/s. Turbine extractions supply enough low-pressure steam for after-heating and final-heating of the district heating water.

It is also possible to receive up to 150 kg/s of district heating water at about 95°C from power plant 2 (OV-2), and heat it to 110-115°C, together with the water produced by OV-5. This solution is adopted because the steam in OV-5 is extraction steam (2.5 bara), whereas the steam in OV-2 is high-pressure steam (6.5 bara) that has been used as possible for electrical production. OV-2 pumps this water through the final heaters in OV-5. In this way OV-5 can simultaneously supply 320 kg/s of 110-115°C hot water to the Njardvik pipeline and 70 kg/s of 85°C hot water to the Grindavik pipeline. Figure 3 shows a flow diagram of the OV-5 power plant.

The turbine is designed to operate at full-load and also supply extraction steam for the district heating system. If the power is reduced, eventually the extraction steam pressure becomes too low to be used for district heating heat exchangers, and, instead of the extraction steam, the high-pressure steam, taken through the bypass valves, must be used to heat the district heating water.

The high steam pressure to the turbine will be controlled by the existing control valves in OV-2. In addition, the turbine will be equipped with a valve that reduces the turbine power if the steam pressure drops below 6.5 bara.

The medium pressure (first extraction) varies with the district heating load, 2.7B 3 bara. If the turbine load is reduced, this pressure drops. In order to maintain minimum pressure, a bypass valve controls steam from the high-pressure steam supply in order to prevent the medium pressure from dropping below 2.5 bara.

The low pressure (second extraction) varies with the district heating load (1.4 bara at maximum and 1.9 bara at the minimum district heating load). A control valve between power plants OV-5 and OV-2 controls the extraction pressure based on a variable set-point that depends on the district heating load as measured by a flow meter. It is assumed that the turbine is run at maximum load (30 MW_e). If the turbine load is reduced, the extraction pressure drops below 1.3 bara at some point. Then a by-pass control valve opens to maintain the pressure at 1.3 bara. At the same time, the check valve reduces the steam coming from the extraction. Chimney valves in OV-2 control the pressure at 1.3 bara at that side, so that the 6 MW_e turbine and the Ormat turbines will not be disturbed because of variability in low-pressure steam in OV-5.

The condenser pressure is controlled by the temperature of the cooling water from the cooling tower. The mixture of condensate water with brine is controlled by two valves that are operated by the same regulator (one opens whereas the other closes).

3. MODELLING

The Modular Modeling System (MMS, Framatome Technologies, 1998) is used to simulate and analyze the performance of the power plant OV-5. It is intended for use during both plant design and operation. The MMS code permits simulation, during the design stage, of a wide range of transients that may occur with a proposed plant configuration, for example as a consequence of a heater pump trip. It can be used for performance analysis of a co-generation power plant at different conditions, such as different conditions of production wells or different thermal and electrical production of the power plant. It also allows us to test alternative control system configurations during the design stage, leading to an optimized design.

The modules in the MMS code are developed from the first principles (conservation of mass and energy) as a lumped-parameter model of components that are recognizable as equivalent to components used in a power plant, such as heaters, turbine, and condenser. For example, a single module representing a reaction turbine stage can be employed several times with different parameter inputs to represent the multi-stage reaction turbine model. The lumped-parameter approach also permits a single component to be represented by different modules at different levels of complexity to meet different modeling needs.

The turbine model simulates ten reaction stages, and a multiple turbine control valve. The turbine is formulated for variable speed operation but the shaft speed is calculated by the generator model. The performance calculations are applicable for speed variations.

Preparation of model parameters is the most important step in the model generation process. The main objectives are to find accurate parameters for each component in the model and to define the model initial conditions accurately enough to bring the model to an initial steady state. The following procedure is used in preparing the parameters of the turbine model (Fig. 2):

Collect Required Physical Data

- Number of control valves
- Number of extractions
- Annular exhaust area

Specify Required Operating Point Data

- Inlet and outlet mass flow
- inlet pressure and enthalpy
- Mass flow of extractions
- Isentropic turbine efficiency
- Condenser pressure
- Steam wetness of each stage

Calculate Required Turbine Parameters

The exhaust enthalpy of a turbine can be calculated by the following equations:

$$h_{out} = ELEP + K_{el} \left(\frac{m_{sl}}{\rho_{sl}} \right)^2 \qquad (1)$$

$$ELEP = h_{in} - \Delta h_{isen} \eta_{isen} \qquad (2)$$

where h is the enthalpy, ELEP is the expansion line end point, K_{el} is the exhaust loss parameter, m_{sl} is the mass flow rate of steam, ρ_{sl} is the steam density, and η_{isen} is the isentropic efficiency of the turbine.

The efficiency of each stage is estimated by the Baumann rule for wet turbine performance, which states that the actual efficiency equals the dry expansion efficiency (assumed to be 0.85), multiplied by the average dryness fraction in the stage.

Check Internal Variables

Some variables such as enthalpy and quality at extraction can be checked to be sure that they are in acceptable ranges.

4. PERFORMANCE ANALYSIS

The utilization efficiency of a geothermal co-generation power plant can be defined as that proportion of the heat input which is utilized as work and heat. The heat input is the difference between the enthalpy of the geothermal fluid (h_r) coming from the well and the enthalpy of the saturated water at reference temperature (h_o). This difference represents the maximum heat that can be extracted from the fluid. The efficiency can therefore be calculated by the following equation:

$$\eta_u = \frac{W_t + Q_h}{m_r\,(h_r - h_0)} \qquad (3)$$

where η_u is the utilization efficiency, W_t is the turbine work, Q_t is the heat output, and m_r is the mass flow rate of production wells. The discharge enthalpy of five deep production wells in the Svartsengi geothermal field has been measured at 1010-1140 kJ/kg (Bjornsson et al., 1998). In the following calculations, 1075 kJ/kg is considered as the average enthalpy of the geothermal fluid and 5°C is used as the reference temperature, which is the mean ambient temperature in Iceland. Figure 3 shows the utilization efficiency of the OV-5 power plant in Svartsengi at different heat loads and 30 MW_e power output. As can be seen, efficiency increases with heat load. This is not due to the increase in thermal output, because the well flow rate (m_r) also increases. The main reason is that the power output is fixed and, therefore, the turbine exhaust flow and rejected heat at the condenser increases. The energy balance calculations show that the utilization efficiency of the OV-5 power plant is improved by 15% using extraction steam

instead of high-pressure steam for district heating.

The energy balance for the Svartsengi power plant is shown in Fig. 4. The main losses are the rejected heat through the brine and cooling water. If the mineral content of the brine permits, the brine can be used to heat the fresh water. But the amount of rejected heat recovered at the condenser is determined by the district heating load and power generation of the plant.

The thermal output of power plant OV-5 is controlled by turbine extractions. Figure 5 shows the temperature distribution through the turbine stages that are determined by the turbine model. In order to heat fresh water up to 95°C and 110 °C by after-heaters and final-heaters, it is necessary to use turbine extractions at 100-110ºC and 115-125ºC, respectively. As can be seen in Fig. 5, turbine extractions between stages 3 and 4 for final-heaters and 5 and 6 for after-heaters provide proper steam for this purpose. The corresponding pressures for these turbine extractions are 2.75 bara and 1.43 bara, respectively, for the full-load power generation (Fig. 6). The turbine model shows that at 24 MW_e rated heat load, the pressure of the first and second extraction drops below 2.5 bara and 1.3 bara, respectively (Fig. 7), and the temperature of the extraction steam approaches the minimum allowable values. At this point, it is necessary to supply enough steam from the main high-pressure steam.

The electrical power of the turbine can be reduced to 21 and 24 MW_e at the medium and maximum heat load, respectively. Table 1 shows a comparison of the turbine model results and the heat balance diagrams of OV-5 at different heat loads. Figure 7 and Table 1 show that the static and dynamic behaviour of the power plant at the different electrical outputs and heat loads can be analysed by simulation.

5. CONCLUSIONS

The total performance of the new geothermal co-generation power plant at Svartsengi is improved by using turbine extractions, instead of high pressure steam, to heat fresh water to 110°C in heat exchangers. Energy balance calculations show that the utilization efficiency of the power plant OV-5 is improved by 15% with this type of operation and by 14-22% at different heat loads.The turbine model shows that at 21-24 MW_e electrical output and different heat loads, the pressure of the first and second extractions drops below 2.5 bara and 1.3 bara, respectively. At this point, it is necessary to supply high-pressure steam to the heat exchangers.

Comparison of the model and manufacturer's results shows that the static and dynamic behaviour of the power plant at different electrical and heat loads can be analysed by the simulation.

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REFERENCES

Bjornsson, G., and Albertsson A. (1985). The Power Plant at Svartsengi. Development and Experience. *Proceedings of the 1985 International Symposium on Geothermal Energy*, Geothermal Resources Council, Davis, pp.427-442.

Björnsson, G., Bjarnason, J.Ö., and Thórdarson S. (1998). Discharge measurements in Svartsengi and Eldvörp in 1996-1997. Orkustofnun, Reykjavík, report OS-98008 (in Icelandic), pp.57-59.

Framatome Technologies (1998). *Modular modeling system (MMS). Basics Manual*, Lynchburg, VA 24506-0935.

Fuji Electric Company (1998). Sudurnes Regional Heating Corporation. *30 MWe Svartsengi power plant 5, heat balance diagram.* C69026-T/YDS-102B.

Gunnarsson, A., Steingrimsson, B.S., Gunnlaugsson, E., Magnusson J., and Maack, R. (1992). Nesjavellir geothermal co-generation power plant. *Geothermics*, Vol. 21(4), pp. 559-583.

Uchida, T. (1997). Geothermal power generation in Japan, *UNU G.T.P., Iceland*, unpublished invited lecture.

Table 1. Comparison of the turbine model results and Fuji heat balance diagrams (Fuji,1998).

Thermodynamic properties	**Maximum heat load**		**Rated heat load**		**Medium heat load**		**Minimum heat load**	
	Model	**Fuji**	**Model**	**Fuji**	**Model**	**Fuji**	**Model**	**Fuji**
m_{in} (kg/s)	85.92	85.29	80.38	80.34	76.46	76.43	72.83	72.99
m_{out} (kg/s)	44.92	44.29	49.38	49.34	55.46	55.43	57.81	57.99
$p_{ext.1}$ (bara)	2.78	2.75	2.91	2.91	2.92	2.88	3	n.a.
$p_{ext.2}$ (bara)	1.47	1.43	1.62	1.62	1.83	1.85	1.92	1.95
$h_{ext.1}$ (k J/kg)	2640	2631	2650	2646	2655	2651	2663	n.a.
$h_{ext.2}$ (k J/kg)	2555	2545	2571	2566	2589	2591	2598	2601

n.a. = not available

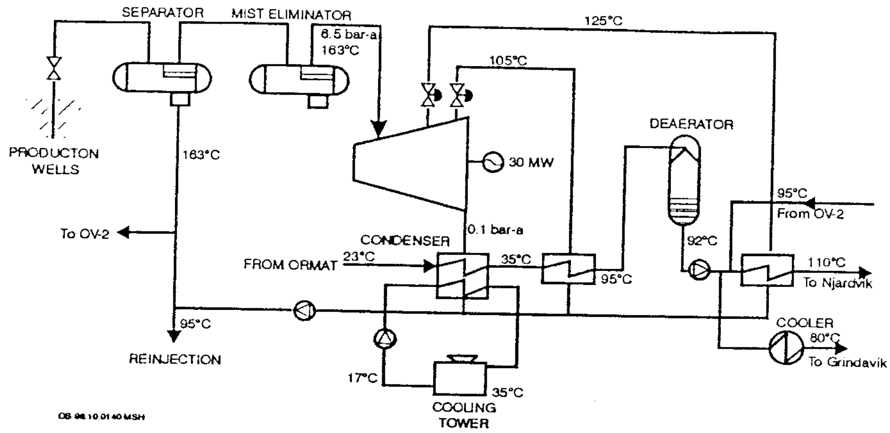

Figure 1. Flow diagram of the power plant OV-5

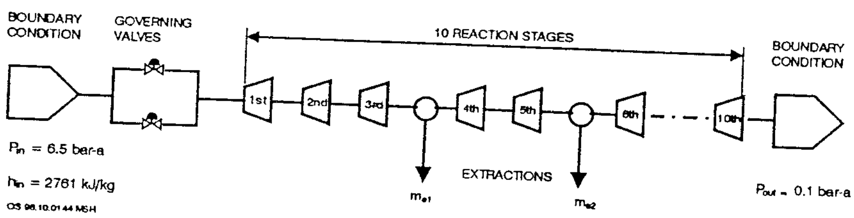

Figure 2. Schematic of the OV-5 turbine model

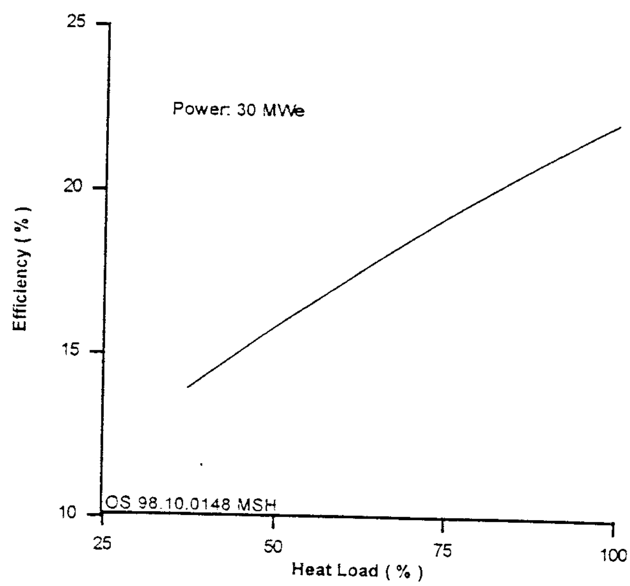

Figure 3. Utilization efficiency of the power plant OV-5

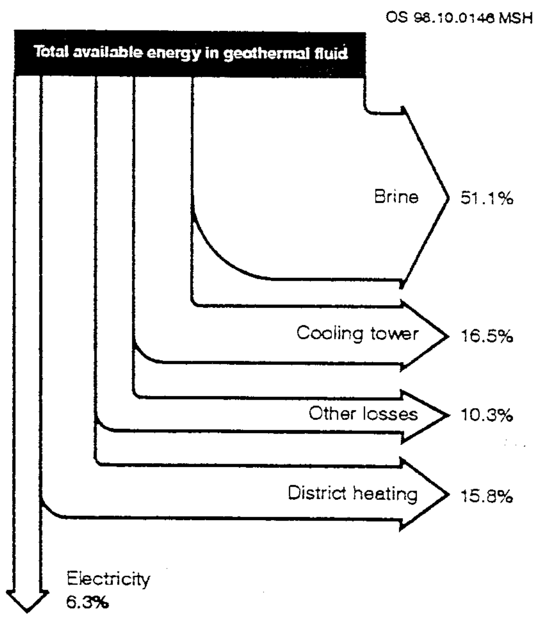

Figure 4. Energy balance of the power plant OV-5

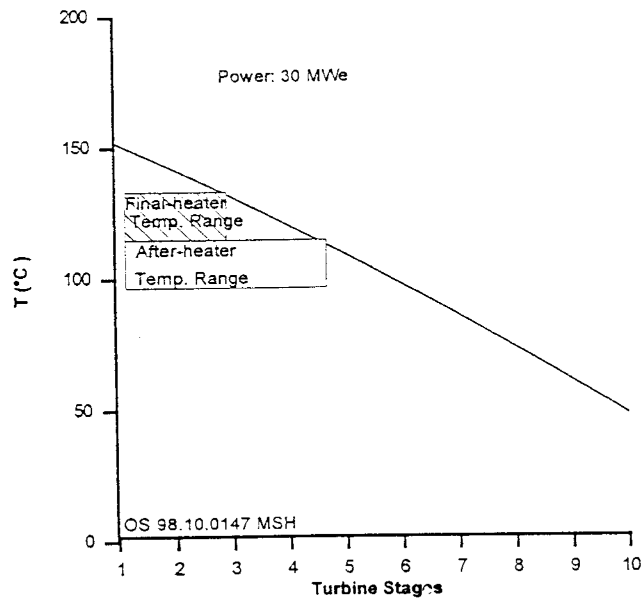

Figure 5. Temperature distribution through turbine stages

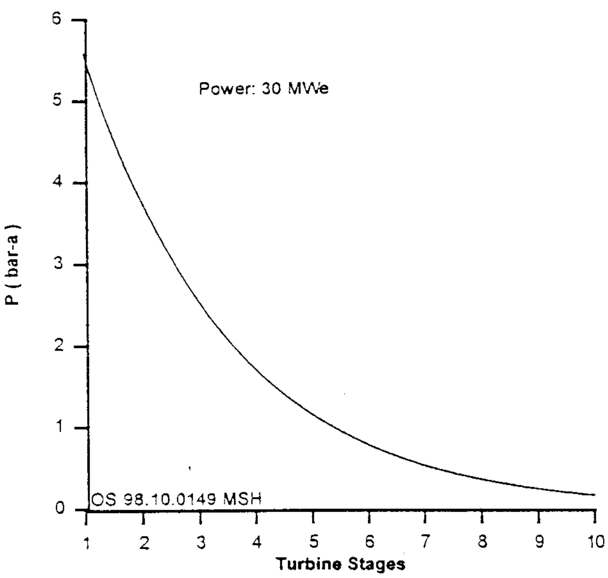

Figure 6. Pressure distribution through turbine stages

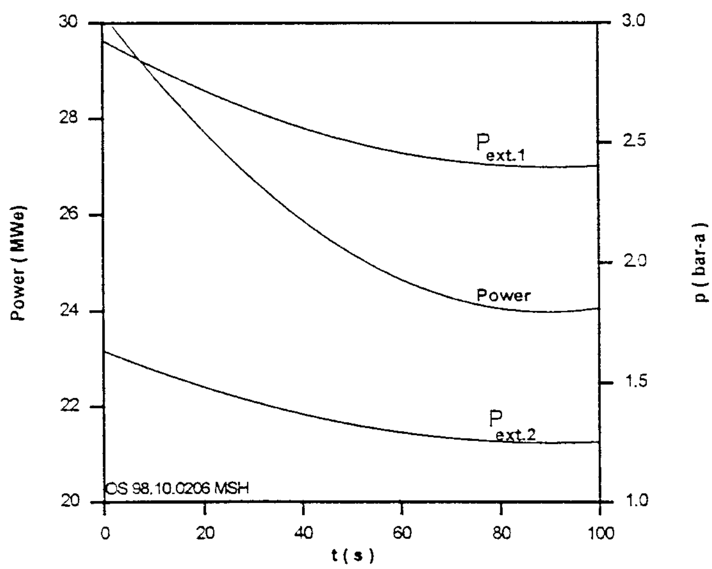

Figure 7. Pressure distribution of extractions at different electrical loads