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EXTRACTION OF GEOTHERMAL ENERGY AND ELECTRIC POWER GENERATION USING A LARGE SCALE HEAT PIPE

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ABSTRACT

In order to utilise low enthalpy natural heat sources, a heat pipe using a binary fluid is a good device which can extract heat without using electric power. When the heat flux in a geothermal bore is moderate, a long heat pipe is needed. We developed a 150 m long, large scale heat pipe of 150mm outer diameter, in which liquid feeding tubes with showering nozzles were installed. It has an excellent thermal performance compared with other long vertical evaporators.
A demonstration test was carried out in a well with temperatures between 100 and 150 ^oC at a geothermal site in Kyushu, Japan. The heat pipe extracted 90 kW heat at a working temperature of 80 ^oC. We also calculated the extraction rate for different lengths of the heat pipe and different temperatures of the geothermal source. Similar pipes can be used for heat extraction of high temperature geothermal fluids .

In addition to heat extraction, we also studied the performance of a turbine which can be installed on top of a heat pipe using a binary fluid. We used a modification of a thermosyphon, with excellent heat and mass transfer characteristics, and incorporated a turbine. The heat transfer in a thermosyphon occurs through the circulation of a binary working fluid through a sequence of evaporation, vapour transfer, condensation and liquid return. It is then possible to convert some of the energy of the vapour stream into electric energy by installing a turbine which is coupled to an electric generator. Simulation showed that a heat pipe turbine, using R-123 as working fluid, can generate about 7.8 kW electric power at a turbine speed of 3000 rpm when the rotor diameter is about 0.8m and the evaporator section of the heat pipe is 150m long. The Heat Pipe Turbine or Thermosyphon Rankine Engine (TSR) is therefore an interesting concept for power generation using geothermal or other low grade heat sources.

1. INTRODUCTION

Utilisation of unused thermal fluids with rather low temperature, such as geothermal waste heat, hot spring water, but also urban waste heat, has been looked at in recent years. As a heat transfer device for otherwise unused thermal fluids, a high performance heat pipe is attractive. However, substantially high performance can not be expected simply by enlarging the diameter and length of a standard heat pipe. In a conventional thermosyphon or heat pipe consisting of a single tube, thermal performance is restricted by entrainment and flooding phenomena. Furthermore, it is difficult to maintain a uniform liquid film throughout a large evaporator which causes the heat transfer performance to deteriorate.
In order to improve the thermal performance, we have developed a large scale, loop type and gravity assisted heat pipe where vapour- and liquid flow passages are separated by installing liquid feeding tubes with showering nozzles inside the evaporator. We have conducted a demonstration test of such a heat pipe at a geothermal site..

2. DEMONSTRATION TESTS OF EXTRACTING GEOTHERMAL ENERGY WITH A HEAT PIPE

A heat pipe is a heat transfer device which can transfer quickly heat from a high temperature section to a low temperature section. Heat pipes are presently used for cooling electronic components, snow melting systems, etc. The heat transfer rate of a simple heat pipe has limitations. In order to overcome these limitations, we developed several loop type structures. We used for initial tests several heat pipes such as a 12 m long, vertical pipe with 46 mm outer diameter and a 70 m long, inclined pipe with 150 mm outer diameter. These types have an up to ten times greater heat transfer rate than a conventional heat pipe. The merits of extracting geothermal heat by using a heat pipe are :
1) No power is needed for extracting and transferring geothermal heat.
2) Even in a dry geothermal well filled with hot air or vapour, a heat pipe can still extract some heat.
3) A loop type heat pipe can control the heat transfer rate by controlling the flow rate of the returning working liquid.

A schematic diagram of our loop type heat pipe with showering nozzles is shown in Fig.1 (Mochizuki et al. 1994). The liquid feeding tubes with a thermal insulator are installed inside the evaporator to create a one way flow loop. Showering nozzles are attached along the liquid feeding tube at a specified spacing to allow uniform spurting of the working liquid. Furthermore, a control valve has been installed at the bottom of the condenser to adjust the flow rate of the working fluid. The corrugated shaped tube with anti-corrosion material was used as an evaporator container.
Geothermal heat extraction was carried out in a well at a geothermal site in Kyushu, Japan, using a 150 m long heat pipe. Before operating the heat pipe, the temperature distribution of the geothermal well was measured;

temperatures at depths from 70m to 150m were between 120 and 150 °C. The heat pipe extracted heat at a rate of 90 kW at a working temperature of 80 °C. This test was sponsored by MITI in cooperation with Kyushu Electric Power Co. We simulated similar tests for different lengths of the heat pipe and for different temperatures of geothermal sources.

3. PREDICTION OF PERFORMANCE OF HEAT PIPES

On the basis of the demonstration test at the Kyushu geothermal site, we tried to predict heat extraction of larger scale heat pipes. Fig.3 shows the results for different fluid temperatures (hot water) inside a well. In Fig.4, results are shown assuming geothermal fluids exist in the well and that their temperature is either 100 or 150 °C; at the higher temperature, 350 kW heat could be extracted using a 300 m length evaporator heat pipe.

It is suggested that a similar type of heat pipe can be used to extract heat from higher temperature geothermal fluids and other heat sources.

4. ELECTRIC POWER GENERATED BY A HEAT PIPE TURBINE

4.1 Heat Pipe Turbine

A Heat Pipe Turbine is a new concept for power generation from solar, geothermal or other available low grade heat sources. It uses a modification of the thermosyphon cycle, which has excellent heat and mass transfer characteristics, and incorporates a turbine in the adiabatic region. The configuration involves a closed, vertical cylinder functioning as an evaporator, an insulated section and a condenser (shown in Fig.5). The turbine is placed near the upper end between the insulated section and a condenser section; a plate is installed to separate the high pressure region from the low pressure region in the condenser. Conversion of the fluid enthalpy to kinetic energy is achieved through a nozzle. The mechanical energy developed by the turbine can be converted by direct coupling to an electrical generator.

The working fluid is located in the lower evaporator end of the heat pipe and flows to the upper region after evaporation. The condenser is situated in the upper region. Here the vapour changes into liquid again and the condensed liquid returns to the evaporator by gravity. Between the evaporator and the condenser, the vapour passes through the turbine.

Akbarzadeh et al. tested the performance of a heat pipe turbine. In their prototype, a reaction turbine was introduced. The diameter of the heat pipe was 160 mm and its height 3.15 m. An electrical power output of 5.5 W at 4788 rpm was obtained from a heat input of 4.4 kW. Another prototype consisted of a cylinder of 2.8 m height with a diameter of 0.5 m.. The heat input was 10 kW and an electrical output of 0.1 kW was obtained at 6000 rpm.

The thermodynamics of such a heat pipe turbine is discussed below.

4.2 Thermodynamics of a heat pipe turbine

Let us assume that $Q^{\bullet}(w)$ is the rate of heat transfer in the evaporator section. This heat can be provided by an external source, such as solar, geothermal, waste, etc. The rate of mass flow of vapour $m^{\bullet}(kg/s)$ generated in the evaporator is then:

$$m^{\bullet} = \frac{Q^{\bullet}}{h_{fg}}, \quad (1)$$

where h_{fg} (J/kg) is the change in specific enthalpy from saturated liquid to saturated vapour in the conditions of the evaporator.

Now let us consider the configuration of the reaction turbine presented in Fig. 4. Assuming that the rotor has a radius of R(m) with a total nozzle exit area of A_o(m^2) and the angular velocity of the rotor is w (rad/s), then:

$$U=Rw, \quad (2)$$

where U is the velocity at the nozzle.

If V_r (m/s) is the relative velocity of vapour leaving the nozzle with respect to the nozzle, the absolute velocity of V_a (m/s) of the vapour with respect to a stationary observer will be given by:

$$V_a = V_r - U, \quad (3)$$

Conservation of mass yields the relation:

$$m^{\bullet} = r_{\circ} V_r A_{\circ}, \quad (4)$$

where $r_{\circ}$ (kg/m^3) is the density of the vapour leaving the nozzle. The torque T (Nm) produced by the flow of the vapour through the nozzle is given by:

$$T = m^{\bullet} V_a R. \quad (5)$$

The produced power $W^{\bullet}$ can then be calculated as:

$$W^{\bullet} = Tw = m^{\bullet} V_a R w. \quad (6)$$

If one assumes an isentropic efficiency k for the adiabatic expansion of the vapour from the condition existing in the evaporator to the condition at the nozzle outlet, then conservation of energy yields:

$$W^{\bullet} = m^{\bullet} k(h_i - h_{\circ}) - m^{\bullet}\frac{1}{2}V_a \quad (7)$$

where h_i (J/kg) and h_o (J/kg) refer to the specific enthalpy of the working fluid at the evaporator and nozzle outlet respectively.

After elimination of the parameters $m^{\bullet}, w, V_r, V_a$ and R in the above equations, it can be shown that the following relations exist:

$$W^{\bullet} = \frac{Q^{\bullet}}{h_{fg}} \sqrt{\left(\frac{Q^{\bullet}}{h_{fg} r_{\circ} A_{\circ}}\right)^2 - 2k\left(h_i - h_{\circ}\right)} * \left[\left(\frac{Q^{\bullet}}{h_{fg} r_o A_o}\right) - \sqrt{\left(\frac{Q^{\bullet}}{h_{fg} r_o A_o}\right)^2 - 2k(h_i - h_o)}\right] \quad (8)$$

and

$$U = m^{\bullet}\sqrt{\left(\frac{Q^{\bullet}}{h_{fg}\, r_{\circ} A_{\circ}}\right)^{2} - 2k\left(h_i - h_{\circ}\right)} \quad . \qquad (9)$$

As an alternative equation for output power the following relation can also be derived:

$$W = r_{\circ} A_{\circ} U$$

$$\left(-U + \sqrt{U^{2} + 2k\left(h_i - h_{\circ}\right)}\right)\left(\sqrt{U^{2} + 2k\left(h_i - h_{\circ}\right)}\right) \qquad (10)$$

By examining equation (9), it can be seen that:

$$A_{\circ} \leq \frac{Q^{\bullet}}{r_{\circ} h_{fg} \sqrt{2k\left(h_i - h_{\circ}\right)}} \quad . \qquad (11)$$

The above relation puts a restriction on the maximum of the total nozzle exit area. This means that for a certain condition in the evaporator and condenser region, in order to be able to generate power the above restriction should be observed. The equal sign in the equation above relates to the condition of a stationary nozzle (U=0) when no power is produced.

Examination of equations (8) and (9) shows that as A_o decreases W_o , U increases. This means that for the same rate of heat input to the evaporator, faster machines require less nozzle exit area and at the same time they produce more power. The theoretical limit for maximum power which can be produced can be obtained from Equation (8) by finding the limit when $A_o \rightarrow 0$. This implies that:

$$\left(W^{\bullet}\right)_{\max} = \frac{Q^{\bullet} k\left(h_i - h_{\circ}\right)}{h_{fg}} \qquad (12)$$

and relates to the turbine rotating at infinite speed.
From the above equation, the maximum efficiency can be obtained :

$$h_{\max} = \frac{W_{\max}}{Q^{\circ}} = \frac{k\left(h_i - h_{\circ}\right)}{h_{fg}} \quad . \qquad (13)$$

For k=1, the above η_{max} will be the Rankine Efficiency.

4.3 Predicted Electric Output of Heat Pipe Turbine when using Geothermal Energy

We also estimated the predicted output of a heat pipe turbine. Several types of working liquids were considered. Finally, we selected R-123 as working fluid because of its high performance efficiency. The pressure performance is good for rotating the rotor of the heat pipe turbine. In Fig. 6, the predicted performance is shown for temperatures of 84 ^{o}C at the evaporator and 36 ^{o}C at the condenser by using R123 as working fluid. At a 3000rpm speed of the rotor, an electric output of 7.8kW has been predicted by utilising 100kW of heat extracted by the heat pipe.

5.CONCLUSION

A heat pipe is an effective heat extraction device which can utilise heat from vacant wells. By using a large scale heat pipe of 300m length, it is predicted that 350kW of geothermal heat can be extracted from a geothermal well filled with fluids of 150 ^{o}C. For a more practical use of this heat, we have shown that electric power can be generated by a heat pipe turbine and that it is possible to generate, for example, 7.8kW electric power from 100kW heat extracted by a heat pipe.

REFERENCE

M. Mochizuki et al. (1994). A Performance of Loop-type Heat pipe having Showering Nozzles. Proceeding of 8th IHPC, pp. 448-451.

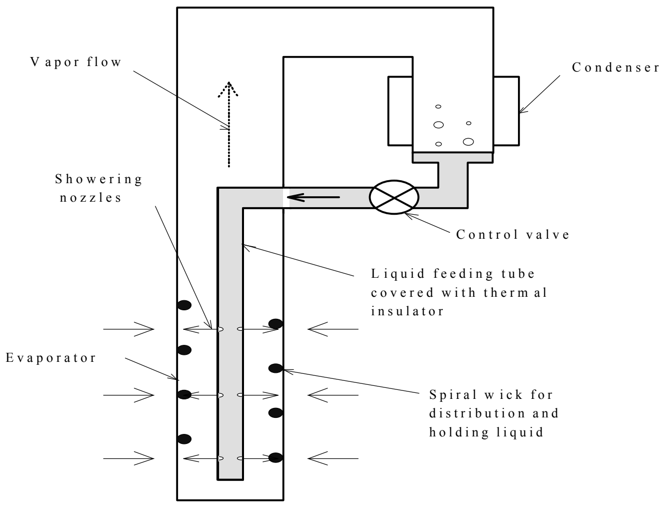

Fig.1: Basic structure of a loop type heat pipe having nozzles.

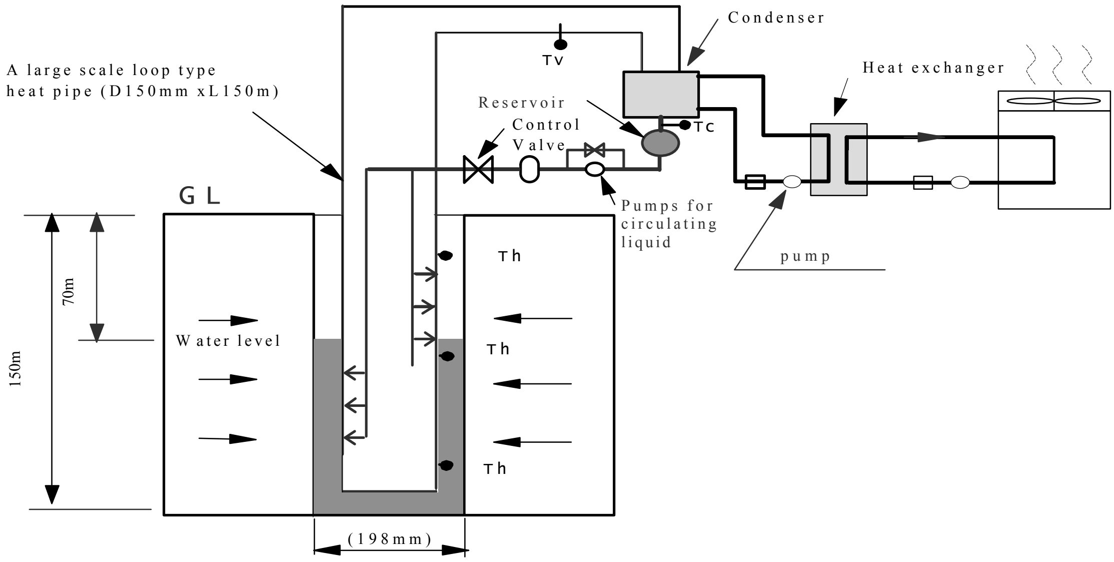

Fig.2: Demonstration equipment used to extract geothermal heat from a well using a large heat pipe

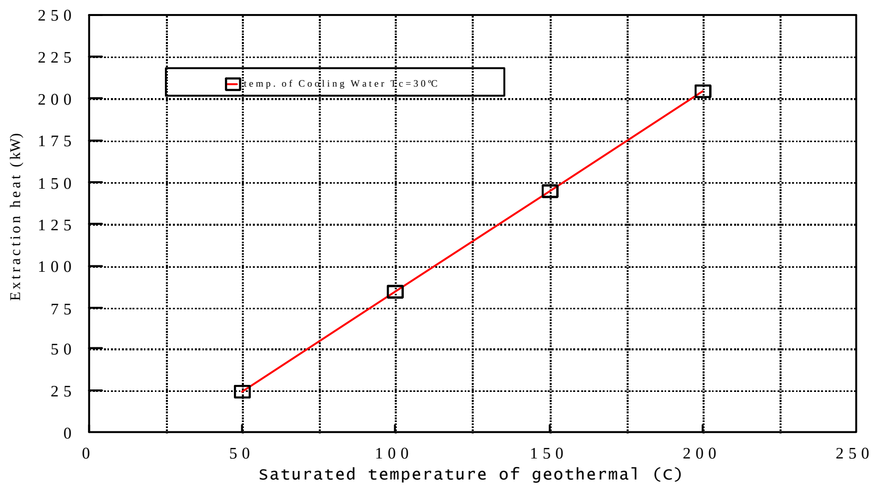

Fig. 3: Calculated results in case of a well filled with hot water

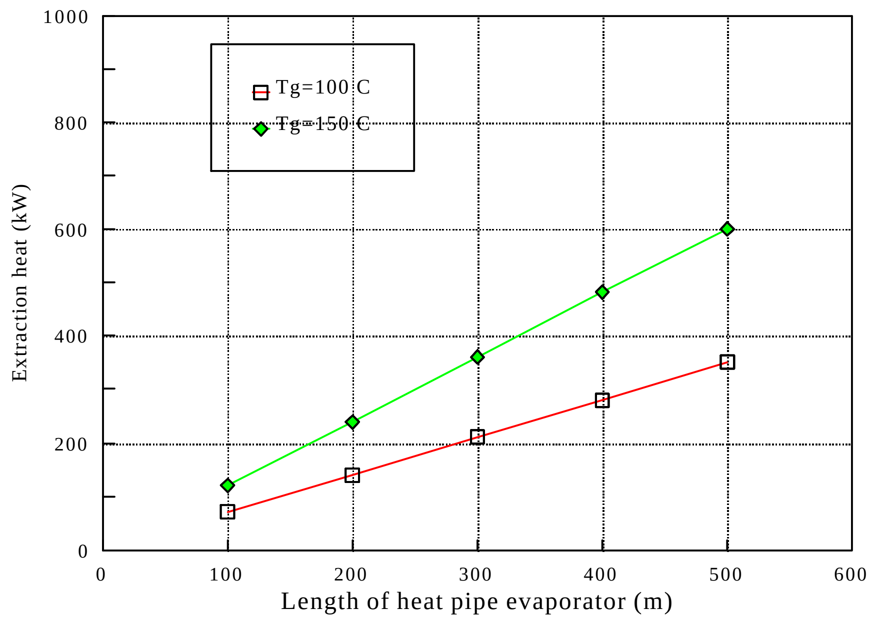

Fig. 4: Extracted heat as a function of the length of the heat pipe

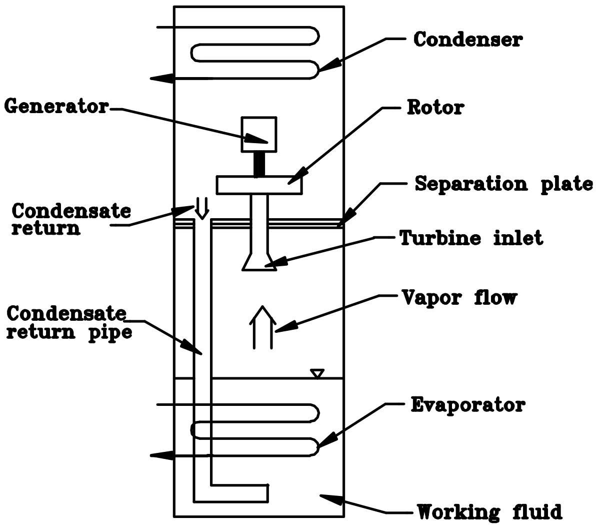

Fig. 5: Schematic diagram of a heat pipe turbine

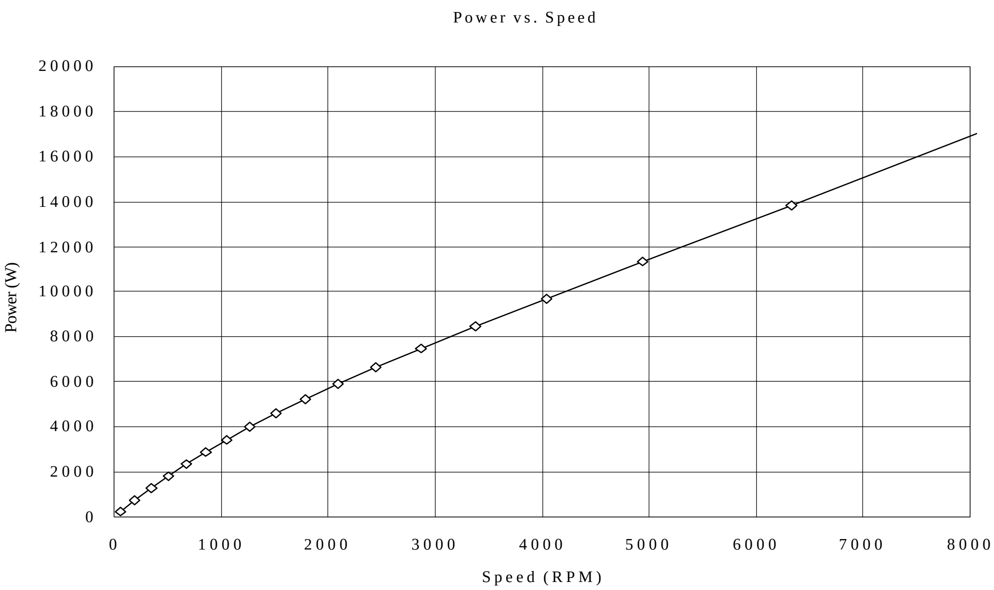

Fig.6: Predicted output of a heat pipe turbine