Combined Fresh Water Production and Power Generation from Geothermal Reservoirs

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ABSTRACT

Using a novel thermodynamic system, utilizing the renewable energy source, electrical power generation and water desalination can be achieved simultaneously, which properly addresses the twin challenges of energy and fresh water shortage. This novel system features a reaction turbine with a pair of convergent -divergent nozzles, which converts the salt water, heated by solar energy, into a mixture of vapour and brine by taking advantage of the trilateral flash cycle. The flashing process occurs in a vacuum chamber which is maintained at a low temperature by an internal coil condenser cooled by water. The reactive force due to the flow exiting the nozzles creates a torque on the rotor arms, which in turn rotates an electric generator and thus generates electrical power. A series of test results such as power generation, fresh water production and system efficiency are presented, which are analysed and also compared with those obtained from the previous experiments. Moreover, a prototype of an improved system is described, which involves a novel disk-shape reaction turbine with a curved flow path for the nozzle, and a new external condensing system that contains four plate heat exchangers. This new system is expected to produce more power, up to 2 kW, in comparison to the current system's maximum power generation of 450 W. In the final part of this paper, the performance of a salinity gradient solar pond and evacuated tube solar water heater as possible renewable energy sources for this kind of system are discussed.

1. INTRODUCTION

Within most areas of Australia the supply of natural fresh water is limited to meet an increasing demand for agricultural, industrial and domestic uses. There are numerous projects underway to supplement fresh water supply where it is needed, for example via desalination of sea-water. The commercially favoured Reverse Osmosis technology for fresh water production from saline water requires large amounts of energy in the form of electricity. At the same time, electricity is presently being generated from predominantly non-renewable and polluting fossil fuels and its generation is largely centralised. Like water, the demand for electricity is also increasing driving an expansion in electricity generation capacity. Environmental considerations relating to climate change and resource depletion are also driving demand for sustainable and lower emission electricity generation technologies as well as decentralised electricity generation to reduce transmission losses. Within this context, Combined Desalination and Power generation (CDP) is a technology of great interest and with potentially high value and wide application (Zhao, 2007).

In the developed CDP system, saline groundwater is first heated by solar collectors to a temperature of 80°C, and then enters a chamber under vacuum, with its pressure maintained at a low level by an internal heat exchanger through which cooling water flows. This hot salt water flashes through a two-phase reaction turbine, featuring a pair of convergent-divergent nozzles (See Fig. 1), the rotor of which is mechanically connected to an electric generator for production of power.

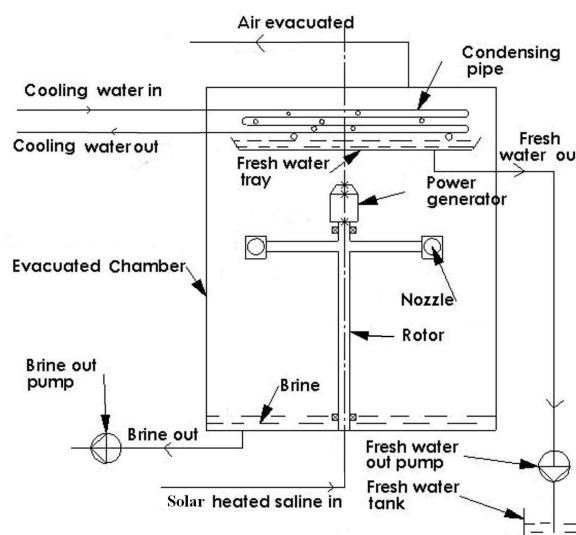**Figure1: Convergent-divergent Nozzle**

Figure 2: Principle of CDP System

As a result of flashing of salt water, a mixture of low-temperature concentrated salt water and water vapor is produced. The vapor is condensed by the heat exchanger to form fresh water that will be eventually collected. While the liquid part of the mixture coming out of the nozzles falls onto the bottom of the tank as saline with a slightly higher salinity. The concentrated saline water is collected, and heated again to repeat the same process, or used as the input to a salt production process.

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The flashing of hot water and the partial phase change causes a substantial increase in the specific volume of the fluid, as a result of which a high-velocity jet is produced at the nozzle outlet. The reaction force as a result of this jet rotates the rotor and hence the generator to produce electrical power (See Fig. 2).

2. The Thermodynamics of the Proposed Combined Desalination and Power Generation System.

The ideal CDP system is theoretically a reversible single-stage water desalination system, whose thermodynamic process (T-s diagram) is shown in Fig. 3. Salt water, at atmospheric pressure and ambient temperature(point 1), goes through a solar water heating system (process 1-2) and comes out at a higher temperature, T_2, but slightly lower pressure due to the pressure loss in the heater. It is then introduced into a vacuum chamber whose temperature, Tc (condenser temperature), is maintained lower than T_2 through a condensing coil heat exchanger. The sudden introduction of the hot water into a cooler and lower pressure environment causes flashing, which results in a mixture of water vapor and brine. Whilst the enthalpy of the mixture is conserved its entropy is increased, as shown in process 2-3a. During this process the water temperature drops to Tc, which depends on temperature of the cooling water flowing through the condensing coil. The process 1-2-3a is a typical process of single stage water desalination. It basically uses the sensible heat available in hot salt water for the phase change needed for production of water vapor and thus fresh water.
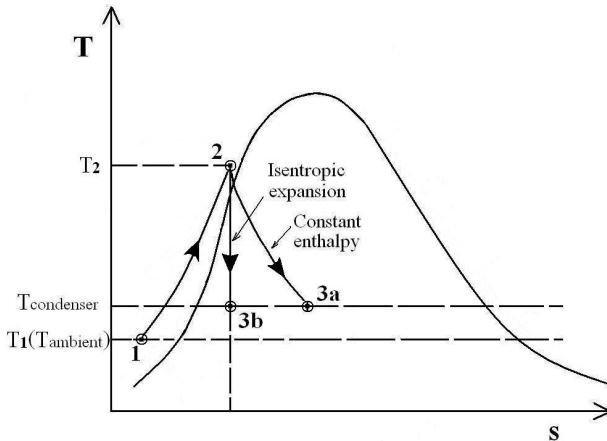
Figure 3: The T-s diagram of the Thermodynamic Process of CDP Unit

As mentioned earlier, the high velocity jets at the nozzle exit exert a large amount of reaction force on the nozzle, which creates torque to rotate the turbine. In order to maximize this rotational kinetic energy, the absolute velocity of the mixture leaving the nozzles with respect to the chamber, Va, should be as low as possible. This means that the tangential speed, U, of the nozzles should be as close as possible to the relative velocity of the mixture with respect to the nozzle outlets, Vr. (See Fig. 4).
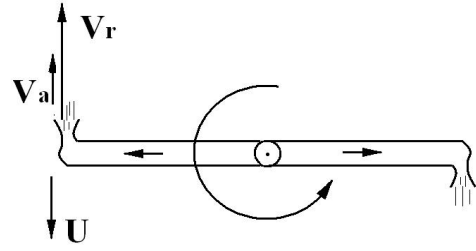

Figure 4: Velocity diagram

3. Design of the Novel Disk Turbine

A new turbine has been made and installed in the CDP unit, which features a novel proprietary design of rotating reaction nozzles. The rotor of this novel turbine has superior mechanical design enabling it to run at substantially higher speeds (See Fig. 5).

There are two significant advantages over the pervious reaction turbine. Firstly, the separation forces (acting laterally to streamwise directions in the nozzles) can be dramatically reduced. Reduction of the separation forces will greatly reduce the slip loss. This large reduction in the separation force is achieved by proprietary curving of the nozzles, as shown in figure 5. Secondly, the new design is expected to have a drastic reduction in abruptness of flashing process. With the previous turbine, passing pressurised water, due to the large amount of centrifugal force, through very short convergent-divergent nozzles causes delay of flashing followed by explosive flashing. Such flashing is inefficient in terms of nozzle reaction forces. In contrast, the novel design effectively avoids the abrupt flashing. First of all, the new nozzles start much closer to the center of the rotor. This minimises the centrifugal force due to rotation of the rotor, which means that the pressure at the nozzle entry is almost the same as the saturation pressure. In addition, the cross-section of the nozzles changes gradually along the nozzle flow path, which results in much more gradual de-pressurisation and flashing (Fabris, 2006). Figure 6 below shows the new turbine installed on the CDP unit.
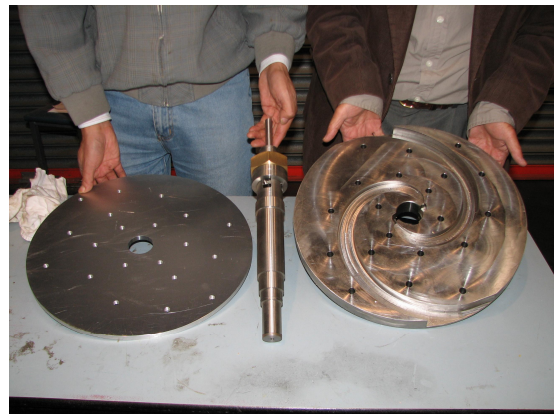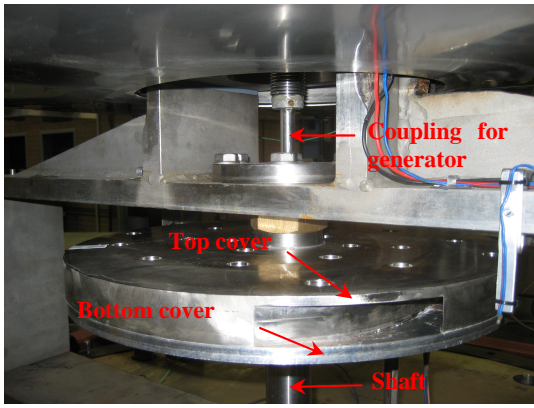

Figure 5: Novel Disk Reaction Turbine

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Figure 6: New Turbine installed on the CDP Unit

3. Test Results and Discussion

The CDP unit has been tested at various electrical loads, with resistance varying from 80 Ω to 250 Ω, in order to find out the optimal load condition which results in maximum power generation as shown in figure 7. It is tested that the electrical power peaks at 440 W, when the load is 100 Ω. This is probably due to the fact that the corresponding rotor speed, about 2350 RPM, is very close to the rated speed of the generator. In addition, based on each performance curve at different load, it is clear that the electrical power produced is directly proportional to the rotor speed.

It has been proved that the CDP unit can work with temperature as low as 60 °C, and that higher the feed water temperature, the higher is the power generation. It is also worth noting that all the tests were carried out under similar conditions, which are 300 kPa of total supply pressure, 100 kPa and 40 kPa of upstream and downstream pressure for cooling water respectively, and 2.22 kg/s of cooling water mass flowrate.
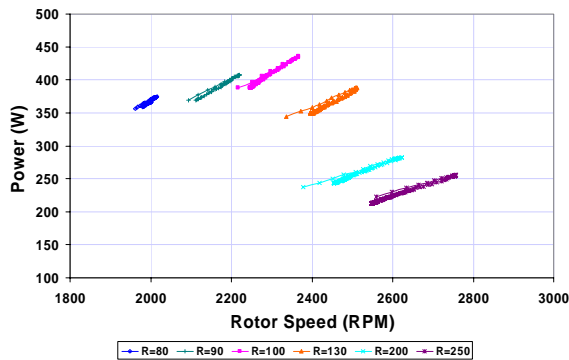

Figure 7: The Performance Curve of Power Generation at Different Load

In Figure 8, the theoretical production of fresh water as well as mechanical energy produced per kilo litre of fresh water is shown as function of inlet temperature of salt water, T_2. Furthermore, Figure 9 shows the required total mechanical energy (theoretical) for pumping the brine and fresh water out of the system as functions of salt water inlet temperature.
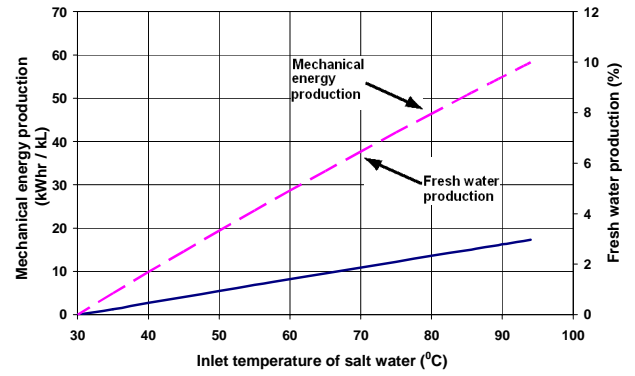

Figure 8: Production of fresh water and theoretical mechanical energy

As seen from figure 8, the production of fresh water and mechanical energy in the CDP unit increase almost linearly with respect to the input temperature. It is illustrated by figure 9 that the required mechanical energy for pumping fresh water can be considerable at low input temperature of water, and it dramatically drops as the inlet water temperature increases. Whereas, the pumping energy for salt water stays almost the same regardless of the inlet water temperature.
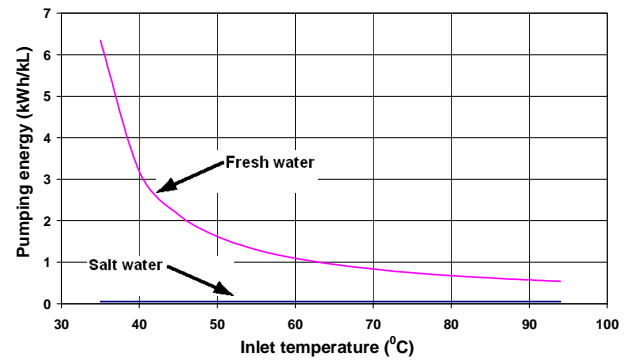

Figure 9: Theoretical pumping energy (kWh) per kilo litre of water
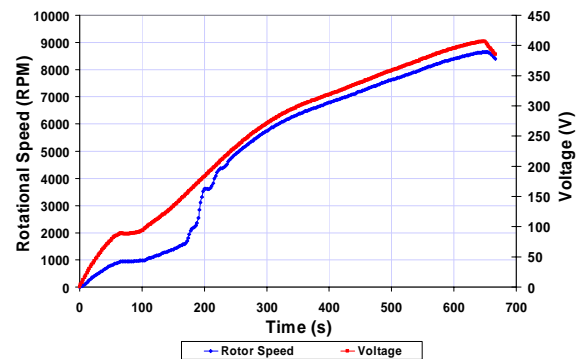

Figure 10: Rotor Speed versus Generator Voltage For the New System

It can be seen from the preliminary results shown in Figure 10, obtained with the new turbine that much higher rotor speed and thus voltage can be achieved, as compared to the old system. The below two figures present the concentrated brine flow rate through the CDP unit with respect to the turbine rotor speed. From figure 12, it is clear that the new CDP system, installed with the novel disk turbine, features a much higher rotor speed, and yet, a lower water flow rate, in contrast to the old system illustrated in figure 11. As a result, this leads to an improved thermal efficiency for the new system.
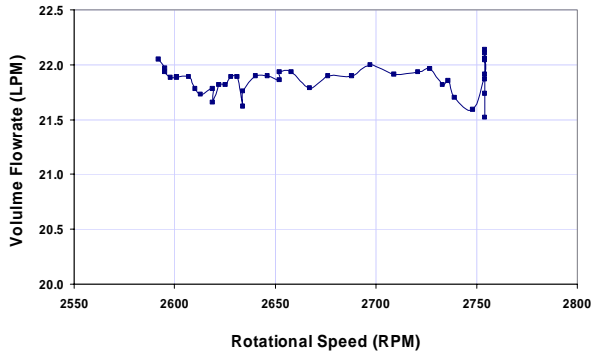
Figure 11: Concentrated Brine Flow rate versus Rotor Speed for the Old System
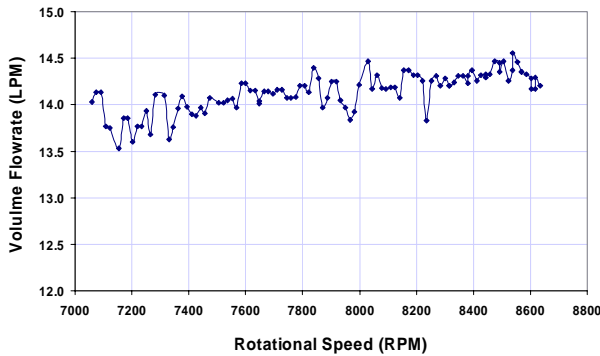
Figure 12: Concentrated Brine Flow rate versus Rotor Speed for the New System

4. Heat Source for the CDP Unit

There is a wide range of solar water heating systems that can be used in conjunction with the CDP unit. Considering the thermodynamics and cost, the temperature of the input water to the CDP unit is anticipated to be less than 100 °C. This means that prospective solar water heating system would be of non-concentrating type. Many solar collectors fall in this category, namely unglazed and glazed flat plate solar collectors, salinity gradient solar ponds and evacuated tube solar collectors.

The efficiency of the non-concentrating type solar collectors can be usually expressed as follows:

$$\eta = a + b\left(\frac{\theta}{H}\right) + c\left(\frac{\theta}{H}\right)^2$$

In the above equation θ is the difference between the temperature of the fluid in the collector and the ambient air

(°C), and H is the flux (W/m^2) of incoming solar energy at the surface of the solar collector.

In the next section, the characteristics of salinity gradient solar ponds and evacuated tube solar collectors, which are two potential candidate to be used as a heat source for CDP unit, will be discussed. Figure 13 shows the solar pond and evacuated tube solar collectors at RMIT University.

4.1 Geothermal Energy

Geothermal energy is heat energy originating deep in the earth's molten interior. The origin of this heat is from primordial heat (heat generated during the Earth's formation) and heat generated from the decay of radioactive isotopes. The total geothermal resource is vast. An estimated 100 PWh (1 x 1017 Wh) of heat energy is brought to the earth's surface each year, however, geothermal energy can only be utilised in regions where it is suitably concentrated. There are four types of geothermal resources: hydrothermal, geopressured, hot dry rock and magma. Of the four types, only hydrothermal resources are currently commercially exploited. Hydrothermal (or hot water) resources arise when hot water and/or steam is formed in fractured or porous rock at shallow to moderate depths (100 m to 4.5 km) as a result of either the intrusion in the earth's crust of molten magma from the earth's interior, or the deep circulation of water through a fault or fracture. High temperature hydrothermal resources (with temperatures from 180°C to over 350°C) are usually heated by hot molten rock. Low temperature resources (with temperatures from 100°C to 180°C) can be produced by either process. Low-grade geothermal resources are relatively abundant and widespread and are located in deep sedimentary basins around the world.

When properly developed and managed, geothermal systems are uniquely reliable, with conventional hydrothermal power stations typically achieving much higher load factors compared to typical load factors for hydro and wind power stations. Geothermal energy is effectively a renewable resource that does not consume any fuel or produce significant carbon dioxide emissions. Hydrothermal power generation from geothermal sources is yet to be commercialised within Australia but has been deployed elsewhere in the world found to be economically viable.

Most geothermal power plants operating today are "flashed steam" power plants using high temperature water from production wells. Others are binary power plants, where energy is transferred via heat exchangers to a working fluid (usually isobutane or isopentane) which boils and flashes to a vapour at a lower temperature than water, so electricity can be generated from reservoirs with lower temperatures. Binary power plants have virtually no emissions but are relatively less efficient.

There are also copious supplies of lower-temperature heat available that are currently wasted, including hot flue gases from industry, and steam and hot water from power stations. Indeed a substantial proportion of the energy content in the fossil fuels consumed in the Australian and other countries' energy systems ends up as 'waste' heat in the temperature range 60 – 100°C. In Australian power stations in 1995-6, around 65% of the primary energy input was lost as waste heat (ABARE, 1997). Heat currently wasted in power stations could in principle substitute for about a third of the total end-use fuel consumption in the

industrial, commercial and residential sectors (Andrews, 1998).

4.2 Salinity Gradient Solar Ponds

Solar ponds are emerging on the renewable energy scene as simple and inexpensive solar collectors for the production of low temperature fluid on a large scale. A solar pond is a body of water in which the natural convection is suppressed. This is achieved by artificially creating and maintaining a density gradient in the body of water. Solar radiation penetrating to the bottom region of the pond is absorbed, and the temperature of this region rises substantially since there is no heat loss due to convection. The temperature difference created between the top and the bottom of the solar pond can be as high as 60 °C. The collected and stored heat can be extracted and used for industrial process heat, space heating, water desalination and even power generation (Akbarzadeh, 2005).

The overall thermal efficiency of solar ponds is generally between 15 % and 20 %. However, it has been shown that if heat is extracted from the non convective zone (middle layer), this efficiency can be increased by 50 % (Andrews, 2005). Figure 14 shows the temperature profiles and its variation with time in a 50 m^2 solar pond at RMIT Bundoora East Campus.

Figure 13: The solar pond (50m^2) and the evacuated tube solar water heating system at RMIT University
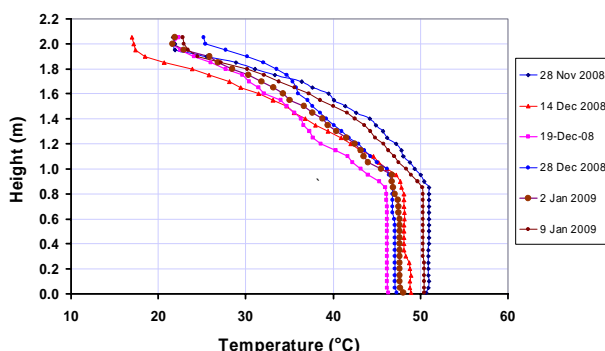
Figure 14: Temperature Profile of the Solar Pond at RMIT

4.3 Evacuated Tubular Solar Collectors

A method to obtain higher temperatures (80 ^{0}C and above) is to use evacuated tubular collectors, in which vacuum is maintained between the inner absorber tube and glazing to suppress the convection losses. These collectors are becoming available at low prices and offer a viable and economical way of solar water heating.

CONCLUSIONS AND FUTURE WORK

Based on the theoretical analysis and experimental tests conducted in this project, the technical feasibility of the combined desalination and power generation (CDP) concept has been proven.

Salinity gradient solar pond can be incorporated as a heat source for the proposed CDP unit. In this case, while the bottom of the pond can supply heat at temperature of 50 to 80 °C, there is also sufficient amount of cooling water available from the upper convective zone for the condenser in the CDP unit. Future work that needs to be done at next stage will be further testing of the CDP unit with the novel disk turbine, in order to obtain better experimental results.

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BRIEF BIOGRAPHY OF PRESENTER

Fulaqi Bai is a postgraduate research student in mechanical engineering department in Royal Melbourne Institute of Technology (Australia). After completing the Bachelor Degree in Mechanical Engineering from the University of Melbourne in 2007, Mr Bai joined the Energy CARE Group in RMIT, and has been doing research study under the guidance of Professor Aliakbar Akbarzadeh. His research project involves power generation, water desalination using renewable energy source, and two phase flow.

Aliakbar Akbarzadeh is a professor in mechanical engineering department and leader of Energy Conservation and Renewable Energy Research (CARE) Group in the Royal Melbourne Institute of Technology (Australia) where he joined in 1986. Prof. Akbarzadeh is actively involved in various projects related to the energy conservation technologies, renewable energy (wind and solar), heat pipes and production of power from low grade sources. He is the author/co-author of more than 75 scientific papers and two books concerned with his research and development in the field of Energy Conservation and Renewable Energy.

Randeep Singh is a research fellow in mechanical engineering department in Royal Melbourne Institute of

Technology (Australia) since 2006. Dr. Singh is actively involved with various projects on two phase heat transfer and power generation from renewable energy sources in collaboration with Fujikura Ltd. Tokyo. His research interests include loop heat pipes, capillary pumped loops, single phase heat transfer, porous structures, solar energy, concentrator photo voltaic and thermo electric generation. He is an author of over 25 research papers published in referred international conferences and journals related to thermal and renewable energy.