Water desalination and power cogeneration utilizing heat pipe heat exchanger

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Abstract. Energy production in Australia is predominantly achieved with non-renewable sources such as coal and natural gas, with up to 86% of national energy being produced by these processes. Further, access to fresh water is fast becoming an issue in the harsh Australian climate. This paper proposes a novel design capable of producing electrical energy and desalinating water using only waste heat from industrial processes. A finned heat pipe heat exchanger plays an integral role in this process, extracting heat from a low-medium temperature waste heat stream and passing it through a thermoelectric generator and evaporative water desalination unit. Preliminary experimentation on this system showed that different desalination loop configurations played a large role in the desalination ability of the system, however had negligible effect on the thermal to electrical conversion efficiency of the system. When a closed loop system was used, the recovery ratio of the desalination unit reached 4% at the highest waste heat temperature. In the open loop configuration, the recovery ratio was below 1% for all tested inputs. The thermal to electrical conversion efficiency of this system was also measured and a value of about 1.2% was determined for most cases. Thus the ability of this novel system to both produce useful electrical energy and desalinate water was proven.

1. Introduction

Freshwater and useful energy are important for the growth of our society, particularly in Australia which produces most of its power through non-renewable methods and has problems with fresh water availability. This is a pressing issue in less developed regions of the country.

Thermoelectric generators (TEGs), in conjunction with desalination, provide an alternative hybrid approach to produce fresh water and power. Modern desalination processes primarily consist of multi-stage flash, multi-effect desalination and reverse osmosis. Multi-stage flash is responsible for 44% whilst reverse osmosis has risen to 42% of global desalination [1]. Multi-stage flash has specific energy consumption between 10-16 kWh/m\textsuperscript{3}, multi-effect desalination between 5.5-9 kWh/m\textsuperscript{3} and reverse osmosis typically requires 3-4 kWh/m\textsuperscript{3} with the inclusion of a recovery system [2]. In terms of the recovery ratio of each process, reverse osmosis tends to lead with ratios as high as 50%, followed by multi-effect desalination between 6-38% and multi-stage flash with less than 6% recovery ratio [3]. As of 2000, the combined world desalination capacity was 22 million cubic meters of water per day, requiring 203 million tons of oil annually as a fuel source [4]. Due to the vast energy requirements that conventional desalination requires, renewable sources typically are overlooked.

In 2012, 6.38 PJ of energy was rejected by the industrial sector as waste heat in the form of effluents and exhausts [5]. Recovery of even 1% of this waste heat is equivalent to over 3,000 tons of CO\textsubscript{2} from coal burning in Australia. The potential for energy recovery is thus clear within the industry.

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Applications of TEGs have grown in the past decade. They have been used for recovery in automotive and industrial applications where the hot waste stream is used to generate electricity. The waste heat is absorbed by a cooling medium on the cold side of the TEG. Orr et al. [6] developed a TEG used for waste heat recovery in automobile exhaust streams. The TEG utilized heat pipes to help transfer heat from the hot waste stream (engine exhaust) to the cooling medium (which could be ambient atmospheric air). A total of 8 cells were used to create the TEG which was able to produce 6 W when charging the battery. The temperature of the waste stream was approximately 200°C at the inlet. This represented a conversion efficiency (thermal to electrical) of 1.43% which was 1/15 of Carnot efficiency at the same conditions.

Orr et al. [7] expanded on this work by introducing high temperature naphthalene heat pipes which only activated when dangerously high exhaust temperatures were experienced. The conversion efficiency in this case was 2.95% with higher waste heat temperatures than the previous work. A similar design of TEG waste heat recovery unit with heat pipe heat exchanger has been investigated by Remeli et al. [8]. Conversion efficiency of 0.7% was reported for this design. Champier conducted an investigation into the current state and application of TEG technology across all sectors, finding that typical TEG devices in use and current research exhibit a maximum efficiency of 5%, with the possibility of 10% being achieved in the coming years [9]. Despite their low efficiency, application toward waste heat recovery could still be beneficial. They are particularly useful when used in conjunction with heat pipes due to the large heat transfer rate associated with heat pipes. The cooling medium is seldom utilized for secondary, co-generative process such as evaporative desalination.

Research has been conducted into the combination of power generative systems with the added benefit of producing fresh water. Date et al. devised a system which utilized flashing of saline water to produce condensate and fresh water in a separate chamber [10]. They produced fresh water at a rate of 1.42 L/m and maximum power of 160 W with the use of a two-phase reaction turbine. Date et al., also proposed a novel waste heat recovery system with fresh water cogeneration. Heat pipe heat sinks and TEGs were used to produce 64 g of fresh water at a peak flux of 24 kW/m² [11].

In this work a waste heat recovery unit consisting of a heat pipe heat exchanger which was capable of both generating electrical energy and desalinating water was built and tested under various conditions. Such a novel design could help in combatting the issues of industrial waste heat and limited access to fresh water.

2. Experimental setup

The proposed power generation and desalination system arrangement is shown in Figure 1. The waste heat stream here was simulated with hot air between the temperatures of 135-275°C. This is regarded as low to medium temperature waste heat and is generally neglected by the industry.

Figure 1. The basic arrangement of the combined waste heat recovery and water desalination system is shown in (a). The waste heat duct is located behind the evaporation chamber. Details of the arrangement are made clearer in (b).
The waste heat duct was well insulated however due to the high temperature of the waste heat it was unavoidable that some heat was lost to the atmosphere.

Integral to the design and operation of this setup was the heat pipe heat exchanger which transferred heat from the hot waste stream, through the TEG and into the saline solution. Four copper-water heat pipes were used in the heat exchanger as seen in Figure 2. These heat pipes had outside diameter and length of 8 mm and 300 mm, respectively. A copper fiber wick was used. The evaporator section of the heat pipes (exposed to waste stream flow) had total of 62 aluminium fins (153 mm x 50 mm x 0.5 mm) with fin spacing of 2 mm. This occupied the entire cross section of the waste heat duct to prevent air from flowing around the heat exchanger.

![Figure 2](image)

**Figure 2.** The heat pipe heat exchanger used in this study had four heat pipes. A fin array was used for the evaporator section (located in the waste heat duct) and the condenser section was embedded in a copper spreader block (located in the evaporator chamber).

The condenser sections of the heat pipes were embedded into a copper spreader block of size 100 mm x 150 mm x 15 mm (Figure 2). The condenser was located in a separate chamber to the evaporator (Figure 1). As shown in Figure 2, this copper spreader block also had an array of six thermoelectric cells on it, which were pressed between the copper spreader block and an aluminium plate (Figure 3). The thermoelectric cells were connected thermally in parallel, but electrically in series. Thermal paste was used to ensure good contact between the thermoelectric cells and the plates. The aluminium plate was maintained at a lower temperature than the waste heat stream by spraying a saline solution over it. The saltwater stream evaporated as it was heated by the aluminium plate and the vapour produced was condensed in a separate area inside the chamber, thus producing fresh water. A condenser coil with ambient temperature water was used to condense the vapour inside the chamber.

![Figure 3](image)

**Figure 3.** The thermoelectric cells were placed between the copper spreader plate of the heat pipe heat exchanger and the aluminium evaporation plate.

T-type thermocouples were present in several locations on the system to measure temperature. A hotwire anemometer was used to measure velocity of air in the duct at various locations and an average air velocity was found for the duct. A variable resistor and multimeter were used to measure the electrical power generated by the TEG. Finally, the amount of fresh water produced was measured with a weighing
scale. These measurements were then used to calculate system performance and efficiency, as shown in the following sections.

The tests were performed at three different average waste heat temperatures of 135, 215 and 275°C, representing low-medium temperature waste heat. A refractometer was used to establish the zero salinity datum of the saline solution used for all tests and then salt was added to a salinity of 1%.

Two different test configurations were trialed; an “open loop” and “closed loop” configuration. The closed loop configuration ensured that the saline solution flowed in a closed loop within the system i.e. once the saline solution flowed over the aluminium plate (where some evaporation had taken place) it would then be recycled to flow over the plate again. In the open loop configuration this was not the case; the saline solution would only pass through the system once.

3. Results

Firstly, the differences between the operating regimes (closed or open loop) will be discussed. It was observed through experimentation that steady state conditions were rarely achieved for the closed loop tests. This was due to the recycling of the saline solution. As the solution passed over the aluminium plate, heat was transferred to it from the waste heat stream (via the heat pipe heat exchanger). This would cause some sensible and latent heating of the solution as observed in the experimentation. Once the solution left the evaporation chamber (slightly warmer than it entered) it was then recycled back to the inlet. During this recycling process, the solution was not allowed to return to its original temperature and thus entered the system again at a slightly higher temperature than what it entered on the previous cycle. This meant that it was very difficult to achieve completely steady state conditions for the closed loop tests. Generally, this test had to be run for several hours until the temperature differences between components was reasonably steady with time, although the magnitudes of the temperature measurements still tended to increase. It was at this point that data measurements were taken and the analysis was conducted. For the open loop tests, steady state conditions were achieved in a much shorter period of time as discussed further below. In these open loop tests, the gradual heating of the saline solution wasn’t an issue as the solution was only passed through the system once and not recycled.

Furthermore, regardless of the loop configuration, it was observed that increased waste heat temperature always lead to increased voltage and power generated by the TEG. This result is somewhat expected due to the general operating principles of thermoelectric cells.

For all tests, the freshwater was collected in the condenser section of the chamber. The salinity of the fresh water was measured by using a refractometer. The refractometer was initially used on fresh distilled water to gauge a datum value, and then salt was added to make the salinity of the solution 1%. After passing through the system, the salinity of the produced fresh water was equal to that of the distilled water before salt addition (according to the refractometer used). Thus the process used here was able to produce fresh water from a saline input.

3.1 Open loop tests

The steady state temperature profile of the 215°C open loop test has been shown in Figure 4. This is included to be representative of all open loop tests as the differences between these tests are only the magnitude of temperature, the trends were the same for all open loop tests.

For this particular test, it took approximately 35 minutes for steady state to be reached (not shown). It can be seen that the temperature upstream of the heat pipe heat exchanger is greater than that of the downstream temperature, indicating that heat is being transferred into the heat pipe heat exchanger from the waste stream. There exists a large temperature difference between the average hot and cold side of the TEG due to the large thermal resistance of the cells. The temperature of the TEG cold side was much larger than the cooling water in the condenser coil (not shown) which caused the migration of water vapour (evaporated from the saline solution) to the colder coil and the consequent condensation of vapour into liquid water, hence fulfilling the objective of water desalination from only a waste heat input. This is significant as many technologies require highly useful electrical energy as process inputs,
whereas this process only required low-medium temperature (often neglected) waste heat as process input. This is an advantage of the current setup.

![215°C Open Loop Temperature Profiles](image-url)

**Figure 4.** The temperature profile of the open loop test at waste heat temperature of 215°C. The trends are typical for all waste heat temperatures for open loop tests.

It can be seen that for this particular configuration, the temperature of the cold side of the TEG was slightly below 100°C, indicating that the majority of phase change of the saline solution was taking place due to evaporation. When the average temperature of the waste heat was 135°C, the TEG cold side was about 60°C indicating evaporation of the solution. At the highest average temperature of waste heat (275°C), the temperature of the cold plate reached 100°C, and flow boiling was beginning to be observed on the aluminium plate. Temperatures above 100°C could not be sustained for the cold plate in this test; it is thought that this was due to the flow boiling over the plate and the large latent heat of the saline solution. As the pressure inside the chamber was maintained at atmospheric, the boiling point of the solution was approximately 100°C (not exactly due to presence of salts). The effectiveness of boiling heat transfer processes ensure that the temperature of the cold plate never raised to a few degrees above 100°C.

In order to assess the effectiveness of the desalination process, the recovery ratio \( RR \) was defined as follows:

\[
RR = \frac{m_{\text{desal}}}{m_{\text{feed}}}
\]  

Here \( m_{\text{desal}} \) is the total mass of the collected fresh water and \( m_{\text{feed}} \) is the total mass of the saline feed water. This was found to be a strong function of the waste heat temperature and generally increased as the temperature of the waste heat increased. The recovery ratio has been summarised in Table 1.

| Waste heat temperature (°C) | Recovery ratio (%) |
|-----------------------------|--------------------|
| 135                         | 0.03               |
| 215                         | 0.11               |
| 275                         | 0.20               |

Table 1. Recovery ratio of open loop systems.
It was observed that the recovery ratio was generally quite small for all open loop tests. This can most likely be attributed to the open loop nature of the test, which meant that cool saline solution was continuously fed into the system and no recycling of the solution was allowed. The saline solution would thus enter the system at around ambient temperature and would have to sensibly heat before undergoing any latent heating. Due to the design of the flat plate evaporation surface, the solution was not allowed sufficient time to change phase which led to the low recovery ratios observed.

In order to assess the thermal performance of the system, measurements of the rate of heat transfer through the heat pipe heat sink and the electrical power output were recorded. The heat transfer rate was calculated from the waste stream as:

$$\dot{Q}_\text{th} = \dot{m}c_p\Delta T$$

(2)

Here, $\dot{Q}_\text{th}$ was the rate of heat transfer, $\dot{m}$ was the mass flow rate of the waste air stream, $c_p$ was the average specific heat of the waste air stream and $\Delta T$ was the temperature difference between the upstream and downstream waste heat air. The thermal to electrical conversion efficiency, $\eta$, was then defined as:

$$\eta = \frac{W_{\text{elec}}}{\dot{Q}_\text{th}}$$

(3)

Here, $W_{\text{elec}}$ is the electrical power output from the TEG. As can be seen in Table 2, large amounts of heat could be transferred through the heat pipe heat exchanger owing to the high effectiveness of the heat pipes. The conversion efficiency, defined as the ratio of electrical power output of the TEG to the heat transfer rate through the heat pipe heat exchanger was generally above 1%. It is unclear to the authors why the highest waste heat temperature test resulted in such low thermal efficiencies and relatively small heat transfer rate; it is believed there may have been a leakage in the system which led to erroneous measurement and poor thermal insulation of the system (consequently large heat losses).

| Waste heat temperature (°C) | Heat transfer rate (W) | Thermal to electrical conversion efficiency (%) |
|-----------------------------|------------------------|-----------------------------------------------|
| 135                         | 375                    | 1.25                                          |
| 215                         | 578                    | 1.10                                          |
| 275                         | 668                    | 0.54                                          |

Table 2. Thermal performance of open loop systems.

Conversion efficiencies of approximately 1% may not seem efficient, but this value is comparable to the values reported in the literature [6-9] for similar systems. This value highlights the potential of this setup. Improvements to the fin arrangement, thermal contact between components and better system insulation could increase this efficiency greatly. Furthermore, the Carnot efficiency at such low heat source temperatures is generally very low. For the lowest waste heat temperature of 135°C, the Carnot efficiency under similar conditions would be approximately 25%. The fraction of Carnot for this scenario is approaching 5%, which is a good result given the temperature of the waste heat.

3.2 Closed loop tests

For the closed loop tests, the temperature profile never completely reached steady state within the tested intervals for reasons discussed previously. Thus the temperature profiles have been omitted here however the trends seen in Figure 4 generally match those seen for the closed loop tests. Further differences were observed for the desalination and power generation capabilities of the system in open and closed loop configurations. Desalination will be discussed first.
As can be seen in Table 3, the recovery ratio for the closed loop systems tended to be larger than for the open loop systems. The reasons for this are simple; in the closed loop system the same saline solution is continually fed over the evaporation plate. Each pass of the evaporation plate causes the saline solution to sensibly heat by some amount. The whole solution is thus heated sensibly and brought up to boiling point temperature whereby phase change will take place. The differences are pronounced at waste heat temperatures of 215°C and 275°C as at these conditions the temperature of the evaporation plate tended to be near the boiling point of the solution, hence flow boiling was often observed and large amounts of solution could change phase and consequently be collected in the condenser section of the chamber.

Table 3. Recovery ratio of closed loop systems.

| Waste heat temperature (°C) | Recovery ratio (%) |
|---------------------------|-------------------|
| 135                       | 1.04              |
| 215                       | 2.28              |
| 275                       | 3.90              |

Clearly, the closed loop configuration is more appropriate from the point of view of desalination as recovery ratios as high as 4% were observed during testing. This is comparable with what can be achieved with a multi-stage flash system [3]. From the point of power generation output, the closed loop system is found to perform very similar to the open loop system. This is shown in Table 4.

Table 4. Thermal performance of closed loop systems.

| Waste heat temperature (°C) | Heat transfer rate (W) | Thermal to electrical conversion efficiency (%) |
|---------------------------|------------------------|-----------------------------------------------|
| 135                       | 353                    | 1.19                                          |
| 215                       | 473                    | 1.19                                          |
| 275                       | 735                    | 0.98                                          |

It is obvious that for the closed loop test, the heat transfer rate tended to be lower than for the open loop tests (we are ignoring the 275°C test as the results of this test for the open loop system cannot currently be explained). This was most likely due to the always increasing saline solution temperature over the evaporation plate. The smaller driving temperature difference between the waste heat and saline solution for the closed loop system meant that less heat could be transferred through the heat pipe heat exchanger overall. In terms of thermal to electrical conversion efficiency, the results of both open and closed loop systems are somewhat similar and it is difficult to make judgement about which configuration provides better operation. It should be noted however that the voltage generated by the TEG was generally smaller for the closed loop tests than for the open loop tests. This was expected to be caused by the gradual heating of the TEG by the recycled saline solution bringing the temperature difference of the TEG sides closer together. This tends to lead to lower output voltages. It was interesting to note that the conversion efficiencies were still similar for both cases, even though output voltage produced were different.

Overall, the performance of the system tested here could use improvement to make it more viable, especially in regards to its desalination ability. Nevertheless the system showed its potential for combined power generation and water desalination. Recovery ratios as high as 4% were observed during testing, and electrical power outputs of 8 W were observed which represented TEG conversion efficiencies of about 1.2% (comparable to values reported in the literature for similar systems).
Integral to the design of this use is the use of heat pipes. The heat pipe heat exchanger was found to very effectively transfer large amounts of heat from the heat source (waste heat stream) to heat sink (desalination water). It was expected that replacement of the heat pipes with equivalent copper tubes would have led to much lower heat transfer rate at the same conditions, and also lower conversion efficiencies and desalination capabilities.

This system is expected to be improved in the future and the authors will report further on the developments. Given the results found from this experimental work, combined with the simplicity, compactness and multi-functionality of the system, further exploration is warranted.

4. Conclusions
In this work, a waste heat recovery unit capable of generating electrical energy and desalinating water was proposed and experimentally tested. Essential to the design of this system was a heat pipe heat exchanger which passed heat through thermoelectric cells (thus producing power) and into a saline solution causing evaporative desalination (in some cases flow boiling was observed). The experimental results showed promising system performance. The recovery ratio of this system reached as high as 4% and was a strong function of whether the system was operated in an open or closed loop configuration. Thermal to electrical conversions efficiencies of 1.20% were commonly observed and were not strongly dependent on the loop configuration.

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