21st Australasian Fluid Mechanics Conference
Adelaide, Australia
10-13 December 2018

Efficient Desalination at Low Temperature Using Low Pressure

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Abstract

This work reports an experimental study of desalination by reducing the surrounding pressure and thus allowing water to boil at low temperature. The water vapour then condenses back into the liquid water at room temperature. The boiling temperature is in the range of 45°C - 75°C which could typically be obtained from a commercial solar water heater. The experimental set-up consists of two cylinders, that could withstand a low, internal pressure; the cylinders are connected by a copper coil that works as a condenser at room temperature. Water that could have been heated by solar energy is introduced into the first tank. A vacuum pump is connected to the second tank, thus directing any water vapour emanating from the first tank to flow toward it via the connecting copper coil. The vacuum pump creates a low pressure throughout and allows the heated water in the first tank to boil. The water vapour thus leaves the first tank, condenses back into the liquid water at room temperature in the connecting copper coil, and drains into the second tank. If seawater is in the first tank, then fresh water would be obtained in the second tank, and desalination has been achieved. It’s shown that the desalination process presented in this work is very efficient in energy requirement. Also, the experimental set-up is simple; and the equipment is readily available.

Introduction

Safe and stable water supply is the major issue for sustainable development. There are more difficulties in securing adequate water supply now than in the past. The construction of reservoirs requires capital costs, the use of groundwater has to consider the treatment cost, and there are also significant costs in surface water treatment. On the contrary, the earth contains 97% of seawater with only 3% of fresh water available in which about 69% are icecaps and glaciers (Veresan, 2015). Therefore, the sea is the inexhaustible resource for drinking water supply. The major commercial technology used in desalination can be divided into two categories, film and evaporation method. The evaporation method includes multi-effect distillation, multi-stage flash, and vapour compression. The membrane method includes reverse osmosis and electro-dialysis. Currently, the most frequent applications of desalination technology in the world are reverse osmosis, followed by the method of multi-stage flash. Nevertheless, both of these two kinds of techniques use extensive energy. Although it seems to have no problem with the desalination technology, however, the process uses a significant amount of energy. This problem will be increasingly concerned about today's environment (Siriwardana, Meng, & McNeill, 2011). Therefore, we consider the use of renewable energy together with the vacuum evaporation method. This can reduce energy consumption. Meanwhile, the concept of sustainable energy use can be implemented through this process. In addition, the process of desalination will emit brine; its salinity is generally two times of seawater. As a result, it will result in mass mortality of aquatic organisms in receiving water. To overcome this dilemma, it is expected that the designed system can reduce the negative effect on the environment for using significant amount of fossil energy or pumping out underground water (Silverstein, 2016).

In the conventional process, desalination is very similar to distillation where salt water is heated to its boiling point and then allows it to condensate. Heating the water to its boiling point requires a significant amount of heat energy which is ultimately produced by fossil energy. In reverse osmosis method, higher maintenance cost is expected as it requires changing the filters very often. Thus, these processes become so expensive raising the cost of fresh water. Underground water is a limited resource of water; rainwater is another source but so much uncertain. Seawater is a renewable resource for that if it can be achieved without significant energy investment. Using water's sensitivity to atmospheric pressure on its boiling point water can be evaporated at a very low temperature and condensed easily by the conventional method. The first aim to get a reliable desalination is to investigate distillation at low pressure. This property has been mainly investigated in this study with the motivation of past studies in this field. Using a vacuum pump and solar heater water desalination must be a cost-effective and sustainable source of fresh water.

Literature Review

Many studies have been conducted for various new methods of desalination. In this research former findings have been investigated and previous drawbacks have been taken into consideration. One of the similar studies to this was ‘Vacuum Desalination by Tower Method’ (Tomahawk, 2015). In this method, the process of Vacuum Desalination takes advantage of the fact that water, when pulled upward by a vacuum, cannot rise more than 33 feet above the level of a surrounding body of water. So, when a tube 50 feet tall (closed at the upper end) is inverted in a body of seawater, and a vacuum is applied, the seawater can only rise to 33 feet. The space above that water is at a very low pressure and can be almost fully evacuated. When the pressure above the water level reaches 0.5 psi, the seawater will vaporise (boil) at only about 29.4 degrees C, which is the ambient temperature in the tropics. Once vaporisation has occurred, the water vapour in the evacuated space can condense on a cold surface within that space, and liquid fresh water is produced on that cold surface. From there, gravity can be employed to collect the fresh water, and pump it to its destination. Though the basic idea of this method (Tomahawk, 2015) is similar to our study, it requires working on eliminating the following drawbacks of this process.

- This process requires near shore installation where the sea depth is 15-20 feet which is sometimes not feasible for diverse weather condition.
- The base of the tower needs to be buried in the sea. This might be disturbed by the sea creature and corrosion

- A minimum construction of 50 feet tall tower is required. Which is also not feasible sometimes near shore for high velocity of wind and diverse weather condition.
- A platformer is required on the top edge of the tower for maintenance. This could require skilled professional and risk is high.
- The process requires an external refrigeration source for condensation. By using the solar collector, if we can raise the temperature of feed water, seawater of ambient temperature can also be used for condensation.
- The pumps used here require electric energy. We can replace it with solar energy.

Nomenclature

Symbol	Description	Unit
T	Temperature	^{0}C
w	Power	W
P	Pressure	kPa
m	Mass	Kg
t	Time	s
W	Energy	J
l	Length	m
V	Volume	m^3
d	Diameter	m
r	Radius	m
A	Area	m^2
η	Efficiency	%
φ	Relative Humidity	%
s	Specific heat of water	kJ/kg-K
ΔT	Temperature difference	K
LH	Latent heat	kJ/kg

The Experiment

A model for experimental setup to apply this idea had been developed in AutoCAD. AutoCAD was used for designing purpose only. The initial model was based on a single cylinder, condenser comprising of cooling plates, freshwater receiver and a vacuum pump. The basic idea was to put some warm seawater around 50^{0}C -70^{0}C inside the cylinder and then close all the valves, start the vacuum pump and raise the vacuum pressure to the required level. The Freshwater receiver should collect the condensed water from the condenser and then stop the process and drain the fresh water and brine. The model had one seawater inlet, one specially designed condenser attached to the vacuum pump and a cone-shaped water catcher to catch the freshwater condensed from the surface of the condenser. The critical point of the model was its condenser. A plate-based condenser was developed to give more exposed area to the evaporated water. Condensation rate would play a vital role in the success of this study so modelling the proper condenser is very important. In the designed condenser there are a bunch of aluminum or copper plates having a small hole to pass the water and vapour. The plates are arranged in a manner that the hole of the upper plate is in the maximum distance from the lower to ensure the condensation of vapour. Also, the plates are slightly inclined to the side of its hole so that condensed water will not get stuck between the plates, due to gravity condensed water should come down through this arrangement (Figure 01). The construction of the condenser as per shown in Figure 01 is still under process and this would be the ultimate arrangement for the condenser.

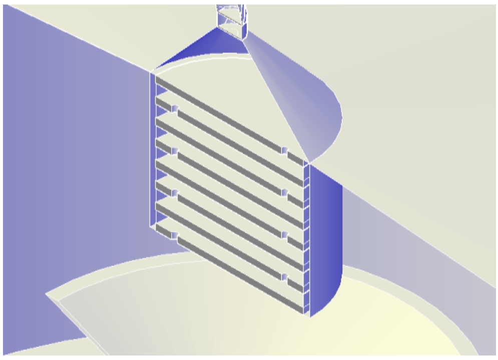

Figure 01 Cross-sectional view of plate-based Condenser in AutoCAD (Diameter of the cylinder is 200mm)

Based on the AutoCAD drawing a test rig was constructed. The test rig consisted of two cylinders, one condenser, one vacuum pump and other required accessories. Both of these cylinders having a diameter of 200mm and length of 305mm were safe and certified by Australian Standards. Gauges, temperature sensors and other fittings were installed on the cylinders.

The first cylinder was the feed water tank where hot water was put. This cylinder was then connected to the condenser. The condenser was connected to the second cylinder. A vacuum pump having a capacity of 0.12 kW was connected to the second cylinder as well. A non-return valve was added between the second cylinder and vacuum pump which helped to retain the obtained vacuum pressure inside the system. Though the AutoCAD design for the condenser was plate based, a very simple type of condenser has been constructed to test the idea (Figure 02).

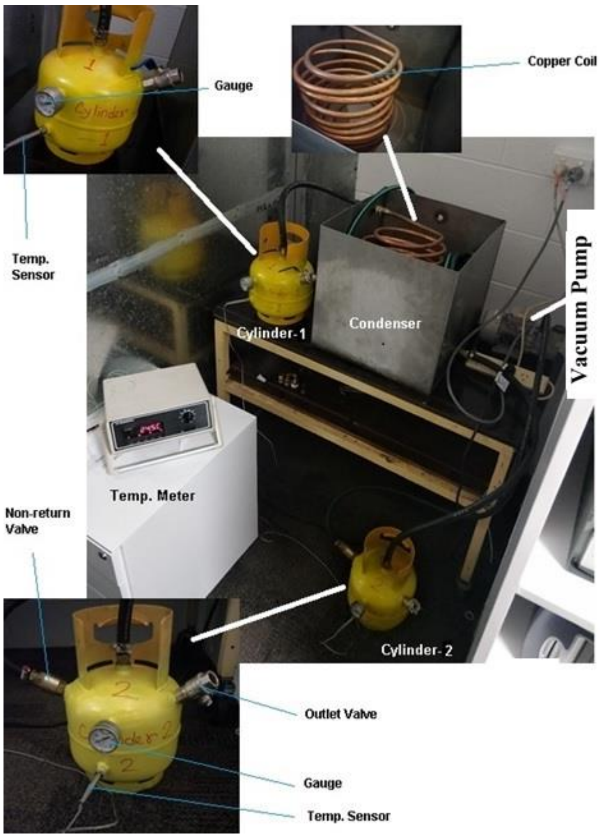

Figure 02 Experimental setup (Cylinder 1 & 2 Diameter: 200 mm, Condenser tank Dimension: 400 x 400 x 400 mm).

A coil was formed with a copper tube which was immersed in water (Figure 02). The coil had twelve turns. The condenser had the similar properties of a shell and tube heat exchanger. The tube had d= 12.7 mm. Following is the schematic of the test rig.

In our experiment, around 2.0 kg of warm water in the cylinder-1 was taken. Then all the valves were closed and the vacuum pump was turned on until we reached our required vacuum pressure. To achieve evaporation at around 25^{0}C, 3kPa absolute pressure inside the cylinders was required. It was achieved by running the vacuum pump and once the vacuum pressure inside the cylinders reached the vapour pressure of water at that temperature, water started boiling (Figure 03). Then the evaporated water passed through the condenser and got condensed and therefore, fresh water in cylinder-2 was achieved.

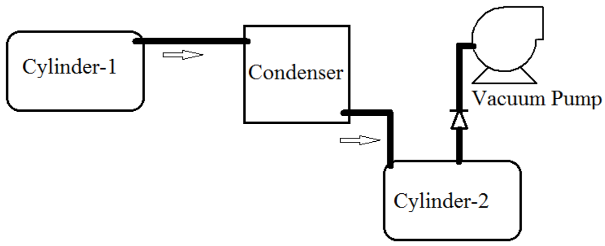

Figure 03 Schematic diagram of the test rig.

Results & Calculation

In an experiment (Table 1), 1.95 kg water of around 74^{0}C was taken in Cylinder-1 and after the process, 0.33 kg of condensed water in Cylinder-2 was found though around 0.4 kg of water from Cylinder-1 was missing.
If we compare the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 1.95 kg
S= Specific heat of water 4.18 kJ/kg-K

ΔT= 80 K

The energy required to heat up 20^{0}C water into 100^{0}C water
= msΔT
= 652.1 kJ

The energy required to convert 100^{0}C 0.33 kg water into 100^{0}C 0.33 kg vapour

= mass x latent heat

= 0.33 kg x 2260 kJ/kg

= 745.8 kJ

The total energy required for getting 0.33 kg of condensed water from 1.95 kg of water in the conventional process is 1397.9 kJ

In this process, water would be heated up by solar energy. So, the only energy required is to create the vacuum pressure only.

The energy required to run the vacuum pump for 120 sec as the required pressure (-97 kPa gauge) was obtained by turning on the pump only for 120 sec = 120 Watt x 120s = 14.4 kJ

Room Temperature (ºC):	20	R Humidity (%):	65
Ambient Pressure (kPa):	101.325	Volume of Cylinder-1 (Litre):	4
Weight of Feed water (kg):	1.95	Volume of Cylinder-2 (Litre):	4
Time	**Feed Water Vessel (Cylinder-1)**		
	Weight of water + Cylinder-1 (kg)	Temperature of cylinder-1 (ºC)	Gauge Pressure of cylinder-1 (kPa)
Before start (Empty)	4.45	20.7	-2
After start (00 min) Pump on	6.4	74	-2
After start (01 min) Pump on		73	-95
After start (02 min) Pump off		68.3	-99
After start (10min) Pump off		43	-99
After start (20 min) Pump off		29	-100
Finish (21 min) Pump off	6	26	-2
	Desalinated Water Vessel (Cylinder-2)		
	Weight of water + Cylinder-2 (kg)	Temperature of cylinder-2 (ºC)	Gauge Pressure of cylinder-2 (kPa)
Before start (Empty)	4.45	20.5	0
After start (00 min) Pump on	4.45	20.5	0
After start (01 min) Pump on		20.5	-97
After start (02 min) Pump off		21	-97
After start (10min) Pump off		24	-97
After start (20 min) Pump off		24	-98
Finish (21 min) Pump off	4.78	24	0

Table 01 Data record of Vacuum Desalination Experiment

% of distillation in our process =

$$\frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1} \text{ x } 100 = \frac{0.33}{1.95} \text{ x } 100$$

Total Energy Savings = $\frac{(1397.9 - 14.4)\ \text{kJ}}{1397.9\ \text{kJ}}$ x 100

= 98.9%

Findings & Discussion

After several testing with different arrangements, this is obvious that water can be desalinated with vacuum pressure. Moreover, to run the process simultaneously a certain amount of heat flow to the feed water is also needed constantly as water will absorb heat from the surroundings when it changes its state from liquid to vapour. This is because of the latent heat requirement of the water to get evaporated. When water changes its state from liquid to vapour, latent heat needs to be supplied to it otherwise it will not be evaporated. For this, warm water of a certain temperature needs to be flown through the feed water tank. In addition, feed water tank (cylinder-1) needs to be at a higher level than the condenser and fresh water tank (cylinder-2) needs to be at a lower level than the condenser to get the help from gravity to flow the condensed fresh water into the fresh water tank. From the experiments, we can say, we need a constant flow of supply water of at least 5º C hotter than the ambient temperature to keep the process running which can be achieved from a solar water heater. We also need to maintain the vacuum pressure inside the cylinders at which water will evaporate (at 5º C hotter than the ambient temperature). Solar energy will be used to retain the supply water temperature 5º C hotter than the ambient temperature during the process. When supply water temperature becomes the same as ambient temperature, though the vacuum pressure inside the cylinders is enough for water to evaporate, this process might not work as the evaporated water will be condensed again in the condenser. The condenser should have a lower or same temperature of the ambient temperature.

Above all following are the key points we can confirm from this study.

- Water can be desalinated in vacuum pressure below 100^{0}C.

- The vacuum pump doesn't need to be operated for the whole process. Once the vacuum pressure has been achieved inside the system it can be turned off and the process will run automatically if we can maintain a flow of warm water of a certain temperature.

- The process requires very low energy consumption and solar energy can warm up the water to its desired temperature.

- A conventional solar water heater can be used to heat up the water to the required level and a continuous flow of this water through the vacuum chambers would be suffice for simultaneous desalination process.

- To utilise gravitational force, condensed water catcher (Cylinder-2) can be placed at a lower level than the condenser.

- The vacuum pressure maintained inside the system should not be same or more than the pressure at which water can be evaporated at the temperature of the condenser. If so condensed water would start to evaporate again or no condensation may occur.

- Normal water has been used in this experiment, but the system should work well with seawater as the characteristics of seawater should not make any fundamental consequence to the experimental process and corrosive consequence to the test rig based on the properties of components which has been discussed earlier. Still, testing with seawater would be done in future work.

Conclusions

Though the test was simple, the findings are very effective to introduce an energy-efficient water desalination system. The aim of this study was to examine a very simple method of desalination and this experiment confirms that such arrangement that has been described here can be utilized for water desalination using only solar energy which requires no periodic maintenance cost.

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