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A novel desalination system for utilizing waste heat contained in cooling salt water of a steam plant condenser

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HIGHLIGHTS

- Developing a system to utilize low temperature heat source.
- Utilizing sea water heat in condensers of steam power plants for desalination.
- Confirming fresh water production capability using optimum system.
- Methodology for predicting the performance of fresh water production capability.

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ABSTRACT

A novel system for utilizing low temperature heat contained in cooling sea water of a steam power plant condenser for desalination is proposed in this work. This system enables warm saline water, leaving the condenser of a steam power plant to flow through a barometer tube to a tight evaporator under vacuum where some water vapor is flashed. The produced water vapor flows to the tip of an inverted U-pipe through an entraining tube connected to the U-pipe due to the pressure difference. The required vacuum is produced by allowing fresh water to flow through the U-tube by immersing each of its two branch terminals in a holding tank full of fresh water. The water levels in the two tanks are at different heights. The brine remained in the evaporator is drained through a drainage barometric tube connecting the evaporator to a brine holding tank. The results of an analytical fluid flow and thermodynamics for predicting the proposed system performance led to infer that relatively high value of producing fresh water rate can be achieved by selecting the appropriate dimensions of the proposed system. For obtaining reasonably high produced fresh water rate (1.5–10.0 kg/h) at reasonably low specific energy consumption (1.0–8.0 kWh/kg) the inner diameters of the U-pipe and entraining tube are selected equal in the range 0.08–0.15 m, and the diameters of the suction and drainage tubes are selected in the range 0.04–0.08 m. Higher values of the produced fresh water rates can be achieved with selected diameters of suction and drainage tubes in the range 0.1–0.16 m, so that any disturbances of water flow through the greater inner diameters of both the U-pipe and entraining tube are obviated, but at greater specific energy expenditure. The height difference of the two fresh water holding tanks is selected in the range of 0.1–0.16 m, so that any disturbances of water flow through the U-pipe are avoided and the specific energy consumption is kept reasonably low. Right choice of the suction and drainage tube heights enables suction and draining the required rate of seawater. They lie roughly 10.1 m depending on their inner diameters.

1. Introduction

Shortage of clean water is continually increasing at different areas in the universe due to population increase and changes in weather. Most of these areas have abundant seawater resources. Desalination is an efficient and well established way whereby these regions can be furnished with fresh water. Desalination of saline water has been practiced regularly for over 60 years [1]. Desalination systems can be classified as phase change technologies (e.g. MSF, MED and VC) and single phase processes (e.g. RO). All these technologies are relatively energy-intensive operations; e.g. MSF, MED, VC and RO consume energy at 19.58–27.25, 14.45–21.35, 7–16 and 4–6 kWh/m^3, respectively [2].

Most regions situated beside seawater sources are supplied with electricity using steam power plants. The condenser of such a plant is

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mostly cooled by means of sea water as a cooling medium, which is circulated through the tubes of the condenser and the exhaust steam of the plant turbine is condensed as it flows over the outer surfaces of these tubes. In this way the cooling seawater absorbs the condensation heat and its temperature increases in the range 8–10 °C. Vast amount of warm cooling seawater is rejected back to sea without any exploitation of its heat content due to the low temperature. If such waste heat is utilized in desalination process the specific energy consumed in producing fresh water will be greatly reduced. Some researchers [3–8] have attempted to employ heat at low temperature for seawater desalination. All these attempts have made use of the availability of temperature difference between two water bodies or flows to evaporate the warmer water at low pressure. The low pressure was created in [3–7] using a vacuum pump, and condense. The resultant vapor was condensed with colder water to obtain fresh water. Operation of the vacuum pump implies the need for a considerable amount of energy which results in a relatively high specific energy consumption. In [8], an educator was used to generate the low pressure. The use of an educator necessitates large amount of motive water flow rate at high pressure. This causes high specific energy consumption.

In [9] a low temperature phase-change desalination process configuration is presented and experimented. Two barometric tubes are used to enable the flow of saline water from a holding tank through one tube to an evaporator situated 10 m above the tank and back through the other tube to a brine holding tank. In the evaporator the saline water is heated by a low grade heat source, where water vapor is formed. The evaporator is connected to a condenser fitted with a third barometer tube, which discharges the fresh water to a third holding tank. The three tanks are installed at ground level. Water vapor flows from the evaporator to the condenser as a result of the pressure difference. It condenses and flows down through the third barometer tube into the fresh water holding tank.

It is to be noticed in the configuration described in [9] that water in the three holding tanks is at the same level. Accordingly the velocities of saline water and fresh water through the barometric tubes are very low and hence the fresh water productivity is very low 0.25–0.3 kg/h [9]. Any disturbance in the flow through the three barometric tubes will lead to stopping the flow in the whole system. This system needs a minimum temperature difference of 15 °C to initiate its operation. This temperature difference exceeds that created by the cooling saline water of a steam power plant condenser (8–10 °C). To overcome these problems and to be able to make use of low temperature difference created by the cooling salt water of a steam power plant, a desalination system is proposed in this paper. The performance of this system is predicted and discussed.

2. Description of the proposed desalination system

The desalination system proposed in the current work is shown schematically in Fig. 1. An inverted U-tube (a) has an inner diameter $d_{u,i}$, and its two branches are of different lengths where the right-hand branch is longer than the left-hand one. Tanks (b) and (c) are filled with fresh water, and tank (b) is located higher than tank (c) where the difference in water levels in them is z_1. The shorter branch is dipped at its inlet into the water contained in the holding tank (b). When closing the valve (g), water flow in the U-tube can be triggered using a pump connected to the shorter branch (the pump is not shown in Fig. 1). As the water flow is established, the pump is disconnected, and water flow continues due to the difference in water levels in the two tanks. Water flows from the tank (b) through the shorter branch of the U-tube and is discharged to tank (c) through the outlet of the longest branch. The top of the U-tube center line (point 3) lies at height z_3 above the water level of the tank (b). The U-tube is connected at this point to an evaporator through an entraining tube with an inner diameter $d_{ent,i}$. An on–off valve (g) is fitted to the entraining tube. When this valve is opened, it allows water vapor to pass from the evaporator (d) to the longer U-tube branch while it stops the vapor flow when closed.

Warm cooling salt water coming out of the steam plant condenser is fed to a holding tank (h). A barometric suction tube (i) with inner diameter $d_{s,i}$ connects the tight evaporator (d) with the tank (h). The lower terminal of the tube is dipped in the warm salt water contained in a tank (h) and the upper terminal is fitted into the evaporator. The pressure in the evaporator (d) is kept below the saturation pressure corresponding to the warm cooling water temperature, by the aid of the pressure regulating valve (j), but it is higher than the pressure at point 3. The height z_7 of brine level with the level of the warm salt water in the tank (h) is adjusted so that the required mass flow rate of warm salt water is induced to enter the evaporator due to the pressure difference between the atmospheric pressure and the pressure in the evaporator. As warm salt water flows and rises through the connecting tube its pressure sinks where eventually some water vapor is flashed in the evaporator. The temperature of water flowing through the U-tube is a bit higher than that of the cool salt cooling water entering the steam plant condenser and coming from a water source (e.g. sea), but it is lower than the temperature of the salt water in the evaporator. The height z_3 is adjusted in such a way that the water at point 3 is in saturation state; i.e. the pressure at this point equals the saturation pressure corresponding to the water temperature in the U-tube. Accordingly the pressure at point 3 is less than that at point 4 (pressure in the evaporator container). Hence, on opening a valve (g), water vapor streams from the evaporator (d) to the longest branch of the U-tube and it runs along with the flowing water down in this branch. As water vapor moves toward the outlet of the longest branch, the pressure increases and as a result, it condenses step by step until it totally converted to water in a short distance as the pressure becomes greater than the saturation pressure corresponding to the water temperature of the mixture of water coming from the shorter branch and condensate. Afterwards the pressure continues to rise until the water flowing through this branch eventually leaves the longest branch of the U-tube at atmospheric pressure.

The temperature of the water flowing out of the U-tube into the tank (c) is slightly higher than that of water contained in a tank (b) due to the condensation of the entrained water vapor and transfer of its latent heat to water. Therefore, water from the tank (c) is circulated using a pump (f) through the tubes of the heat exchanger (e) where it is cooled by discarding heat to the salt cooling water coming from the salt water source. The temperature of cooling salt water exiting the heat exchanger (e) is slightly raised. It is fed to the condenser of the steam power plant directly or after mixing with extra fresh salt water coming forth right from the salt water source for cooling purpose. The brine which remained in the evaporator is drained through a drainage tube (k) to the brine holding tank (l), from which the brine is discharged back to the sea water source. The brine drainage tube has an inner diameter $d_{b,i}$. The level of brine in the evaporator lies at a distance z_8 from the brine level in the tank (l).

3. Prediction of the performance of the proposed desalination system

In this section, a simple analytical analysis for fluid flow and thermodynamics is presented, for predicting the performance of the proposed desalination system. In developing this analysis, the following assumptions are made:

1. The effect of the U-tube bend is neglected and its two branches are considered straight. Therefore the lengths of the left-hand branch (short one) and the right-hand branch (longer one) are considered as z_3 and $(z_3 + z_1)$, respectively.
2. All minor pressure drops in the U-tube are neglected.