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A desalination method utilising low-grade waste heat energy

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ABSTRACT

A new desalination method was proposed in this work, utilizing low-grade waste heat from the power plant, allowing co-generation of fresh water with electricity. The desalination system analysed in this study makes use of simple concepts, such as Torricelli vacuum, flash evaporation and siphon effect, to reduce the overall operating power consumption of the plant. An experimental plant has been built and tested in an existing thermal power plant at Chennai, India. The plant utilized the warm saline reject water from the power plant condenser to feed the evaporator without using a separate feed water pump. The amount of freshwater produced by this plant is nearly 1/200 times of the sea water supplied for the available temperature gradient of 8.7˚C. It is a low-cost system when compared with conventional desalination technologies, with energy consumption per unit volume estimated at 2.62 kWh/m^3 of fresh water generated. It operates at low temperatures, low pressure conditions and produces fresh water of excellent quality. The successful operation of the plant has provided valuable experience and information related to the behaviour of the proposed desalination system.

Keywords: Desalination; Vacuum; Low-grade energy; Waste heat; Co-generation

1. Introduction

Core necessities like water, energy and a clean environment are vital for the sustainable development of society and hence, they are rightly referred to as life support systems. Water is consumed for daily use by people for drinking, hygiene and cleaning purposes. It is also used by power plants, industries and other manufacturing processes. While the demand for freshwater grows, the supply seems to be dwindling and hence, desalination of sea water becomes an essential alternative to cope with the demand.

Fresh water production by desalination of sea water is an established method. However, existing desalination processes have been energy intensive as the feed sea water temperature needs to be raised to its boiling point for water vapour generation. The heat has to be supplied from a source whose temperature is higher than the boiling point of the feed sea water. Further, it requires a large amount of energy to run the pumps for brine blowdown, recycling, heating, condensed steam pumping and chemical dosing, in

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addition to the pumps' requirement for the intake of sea water, cooling sea water and distillate.

The proposed desalination process is designed to make use of the power plant condenser reject waste heat for producing fresh water. The head required to supply sea water to the evaporator and the latent heat of vaporization is taken up from the feed sea water itself. This process helps in decreasing the temperature of discharge sea water that is dumped to sea. The energy is required only to pump the surface sea water for condensing the generated water vapour in the evaporator. This study brings to focus the possibility of using the heat of the condenser reject water from a process plant for a low-energy desalination system.

2. Utilisation of waste heat energy resources

The efficiency of a typical thermal power plant is reported to be around 50%, limited by the Carnot's efficiency, which is governed by the second law of thermodynamics. This explains that for every megawatt of electricity generated, roughly a megawatt of excess heat is rejected, mainly through the power plant condenser. The discharged condenser coolant (surface sea water), which is at a slightly higher positive head, is passed through the cooling towers or heat-dissipating open channels to get cooled before being sent to the sea. An efficient way to utilize the head available in the power plant condenser reject water is to feed the evaporator with certain quantity of heat to produce freshwater, which in turn cools down the discharge sea water.

Sowit, with a grant from the European Community, operated an experimental desalination plant utilising the power plant condenser reject sea water at 8˚C above ambient temperature at ENEL power station, Piombino, Italy. The steam from the power plant is used to maintain the low pressure in the major plant components and not preheat the feed sea water [1]. The National Institute of Ocean Technology constructed and operated an experimental desalination plant using the available thermal gradient of 8.5˚C in a thermal power plant at Chennai, India [2]. The plant is located about 12 m above ground level to ensure the flow of non-evaporated discharge sea water to the main sea water outlet line. One of the major drawbacks of these plants is that the head available in the power plant discharge water has not been utilised properly. It requires a separate sea water pump to feed the warm saline water to the evaporator. The main objective of the present study is to design, develop and operate an environment-friendly desalination plant for the continuous generation of freshwater using low-grade energy in the power plant condenser reject heat, without losing energy for any additional devices such as feed water pumps.

3. Design concepts

Fig. 1 shows a simplified process scheme layout of the proposed desalination system which is designed to utilize the sea water from an existing power plant piping network. Here, the head spaces of the evaporator and liquefier are occupied by the vapours of the respective fluid. These head spaces are connected to one another through a connector pipe called "vapor duct" to transport the generated vapour from the evaporator to liquefier. As the vapour pressure of sea water is higher than that of pure water, the water vapour from the evaporator distills into the liquefier. Hence, the feed sea water temperature entering the evaporator need to be higher than that of the liquefier to raise the vapour pressure of the evaporator above that of the liquefier.

To achieve this in actuality and to drive this proposed desalination system, a low-temperature differential itself is sufficient that can be obtained from the waste heat of a process plant or a nuclear research reactor or other renewable sources such as solar, ocean, thermal or geothermal energy. The proposed desalination system discussed here uses the power plant condenser reject sea water from an existing thermal power plant and surface sea water to feed into the evaporator and liquefier respectively.

This desalination system makes use of the following three well-known concepts effectively to reduce energy consumption for the generation of freshwater.

(1) Torricelli's vacuum (also known as barometric column),
(2) Flash evaporation,
(3) Siphon effect.

3.1. Torricelli's vacuum

The present desalination plant achieves low pressure by Torricelli's vacuum, otherwise known as "barometric column". Warm sea water at a higher temperature rejected from the power plant condenser and the surface sea water which is at a relatively low temperature form two working fluids in this system. The level of the warm feed sea water in the evaporator is maintained at 10.33 m, which yields one atmospheric pressure at sea level. The water column inside the pipe is then allowed to fall under the effect of gravity, creating a low pressure above the water

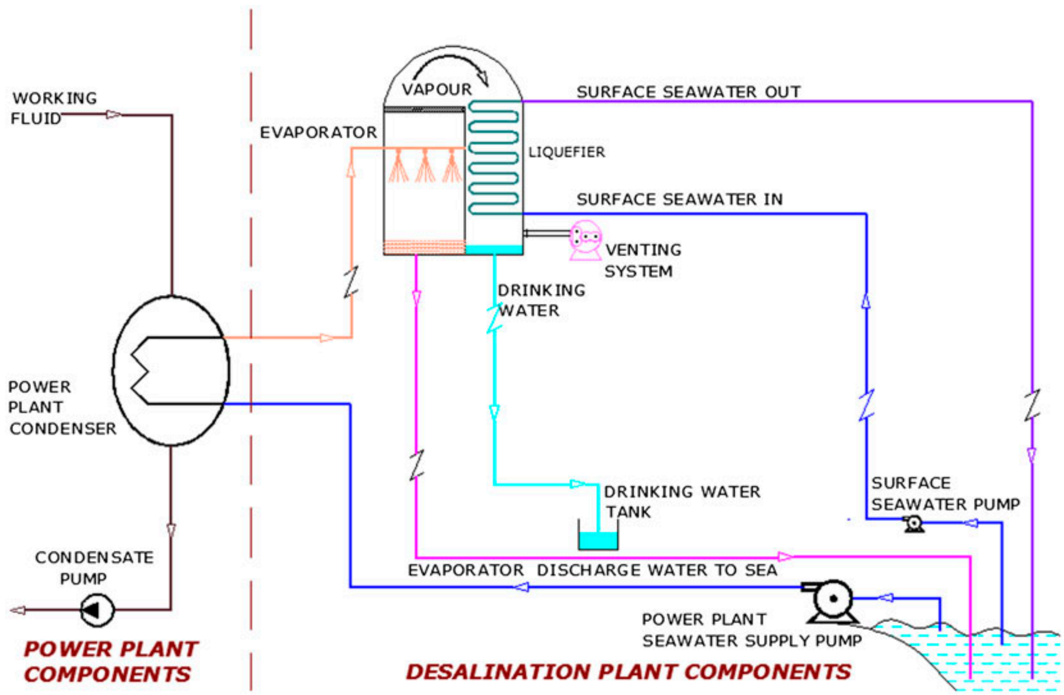

Fig. 1. Process scheme layout of the proposed desalination plant.

surface. The vapour pressure in the evaporator above the liquid surface is determined by the distance between the sea water level in the evaporator and the ground level. Maintaining initial water heights greater than 10.33 m will not result in increased vacuum levels any further, but will unnecessarily increase capital cost in the form of increased plant support structures.

3.2. Flash evaporation

Desalination by evaporating saline water can be effected in two ways viz. (1) by decreasing the system operating pressure in order to bring down the boiling point of water or (2) by increasing the temperature of the saline water towards its boiling point, at a given operating pressure. In the presently adopted desalination process, the system operating pressure is decreased to reduce overall energy consumption. The main reason for this choice is due to the fact that the energy required for water boiling is more than creating low pressure. Further, the cost involved in constructing equipment that is used in decreasing the pressure to effect the phase change is negligible when compared with that involved in boiling the water, where expensive alloys are involved due to increased temperature [3].

The operating principle in the proposed desalination process is that when a liquid at a particular temperature is expanded suddenly in a closed chamber maintained below its saturation pressure, its saturation temperature drops below its actual temperature. Thus, the sea water temperature in the chamber becomes larger than its own saturation temperature and this surplus sensible heat in the water is utilized in the form of latent heat of vaporization, generating water vapour. Thus, a part of the liquid breaks into vapour until the liquid temperature drops and reaches a thermal equilibrium. Here, the process of liberation of the heat is so fast that the sea water flashes into steam and hence, this is known as “flash evaporation”.

3.3. Siphon effect

Siphon arrangement has been adopted to make the surface sea water to flow into the liquefier, reducing the pumping power requirements. A connection to the tube side fluid of the liquefier is made from the venting system. Initial suction of surface sea water into the liquefier tubes is carried out by the venting system. Once the surface sea water starts flowing inside the liquefier tubes, this line is shut off and subsequent flow is maintained by the siphon effect. This helps in decreasing power consumption. Further, it makes use of gravity to discharge the non-evaporated feed sea water from the evaporator without any pumping assistance.

4. Theory

4.1. Sea water head requirement to reach evaporator

According to the first law of thermodynamics, the general energy equation can be written in the form of heads consisting of elevation, velocity and pressure. However, in reality, there is a major loss in head due to friction caused by the walls of the pipe and a minor loss due to spouts, bends, entrance, exit effects, valves and other component fittings. Accounting the head losses, Bernoulli's equation can be written as in Eq. (1).

$$Z_i + \frac{v_i^2}{2g} + \frac{p_i}{g\rho_i} = Z_0 + \frac{v_0^2}{2g} + \frac{p_0}{g\rho_0} + \frac{kv^2}{2g} + \frac{4flv^2}{2gd} \quad (1)$$

This equation can be applied to calculate the head required for the unit flow rate of sea water to the evaporator. The head required is mainly dependent on the pressure maintained in the evaporator, as the atmospheric pressure is taken as constant (1.01325 bar). Thus, a low pressure in the evaporator, increased pipe diameter and reduced number of pipe fittings will lead to a minimised head requirement.

4.2. Heat and mass balance for the system

Considering all modes of heat transfer such as conduction, convection, radiation and phase change between the sea water liquid droplets and surrounding vapour interface, the energy balance equation can be written as in Eq. (2) [4].

$$\left(\dot{m}_{\mathrm{rw}} C_{\mathrm{p}} \mathrm{d}T_{\mathrm{l}}/\mathrm{d}t\right) = \pi D^2 h(T_{\mathrm{l}} - T_{\mathrm{D}}) + \pi D^2 \sigma\varepsilon\left(T_{\mathrm{l}}^4 - T_{\mathrm{D}}^4\right) + \left(h_{\mathrm{fg}} \mathrm{d}m_{\mathrm{fw}}/\mathrm{d}t\right) \quad (2)$$

At the interface of the sea water droplets and vapour, the temperature of the vapour and water are assumed to be equal, so convection effects are negligible. Since the evaporator is evacuated, radiation effects can be assumed to be negligible. Further, it is assumed that the latent heat of vaporization of sea water is taken as 2,420 kJ/kg and the specific heat as 4 kJ/kg-℃ [5]. Because of the low range of temperature differences across the power plant condenser, the value does not vary significantly for different operating conditions. Thus, by considering the phase change alone, after rearranging and substituting the corresponding values, the ratio of mass flow rate of fresh water to the mass flow rate of power plant condenser reject water can be expressed in terms of the temperature difference of feed sea water. This is given in Eq. (3).

$$\dot{m}_{\mathrm{fw}}/\dot{m}_{\mathrm{rwi}} = (T_{\mathrm{rwi}} - T_{\mathrm{rwo}})/605 \quad (3)$$

This shows that for every 1℃ drop in power plant condenser reject water temperature across the flashing process, approximately 0.17% of feed sea water can be vaporised. This estimate yields that 200 kg of feed sea water need to be supplied to the evaporator to produce 1 kg of fresh water when the temperature difference is 3℃. This means that the temperature of the feed sea water at the evaporator outlet will be 3℃ cooler than the corresponding inlet temperature. The same is also true for the liquefier, where by condensing 1 kg of water vapour, the temperature of the surface sea water increases by a similar magnitude, assuming that there is no other form of thermal loss. Hence, the pumping ratio can be estimated as 200:1 for this plant for a given temperature difference of 3℃. Accordingly, the energy consumption for the surface sea water pump per unit volume of fresh water produced by this process can be calculated as shown in Eq. (4) [6].

$$E = \rho grH/\eta \quad (4)$$

5. Description of the proposed experimental desalination plant

The proposed experimental desalination plant was installed in an existing coal-based power plant at Chennai, South India. The reject sea water is available at a positive pressure head of about 2 m at the location where it is tapped from the power plant's condenser discharge line. The typical temperature of this reject sea water is 8.7℃ higher than the ambient temperature.

The main components of the desalination system are:

(1) An airtight barometric sealed flash evaporator to generate water vapour,
(2) liquefier that contains the tube bundles to liquefy the vapour,
(3) connector pipe (vapour duct) to connect the vapour spaces of the evaporator and liquefier,
(4) pump to draw surface sea water for condensation and
(5) pipelines to draw power plant condenser reject water for evaporation.

The evaporator is a closed vessel and the volume is designed to suit the drawn reject water from the power plant condenser to evaporate. This is made of carbon steel with stainless steel internal lining. The liquefier is a shell made of carbon steel with food-grade epoxy coating and tube heat exchanger consisting of tube bundles made of copper–nickel alloy. Both the evaporator and liquefier are designed as a pressure vessel and stiffeners are provided at both circumferential as well as longitudinal directions.

Fig. 2 shows the CAD model of the plant and Fig. 3 shows the pictorial overview of the desalination plant installed in the power plant. The evaporator is located at a height of 10.3 m above the ground level and is maintained at a pressure less than the saturation pressure of the feed sea water. The plant draws a small quantity of power plant condenser reject sea water to the evaporator through a tank placed at ground level. The water level in the tank is maintained constant. Any entrapped air coming from the outlet tunnel along with the sea water is released in the tank and ensures that only sea water enters the evaporator. The available positive head is sufficient to overcome the associated friction losses in the piping and fittings. Hence, a separate feed sea water pump for the evaporator is not necessary. The non-evaporated sea water from the evaporator flows through a pipe to the discharge tank kept at the ground level by gravity. The tail end of the evaporator delivery pipe is immersed in the discharge water tank for effective barometric sealing. During the operation of the plant, any rise in water level in this tank will be allowed to flow to the sea through an open channel.

Fig. 3. Pictorial view of the desalination plant installed in the power plant.

Surface sea water is pumped to the tube side of the liquefier to condense the vapour. The surface sea water pump used here is the main source of power consumption in the plant. A venting system consisting of an oil ring mechanical system is connected to the shell side of the liquefier. It is used to remove the non-condensable gases that get released from the feed sea water in the evaporator during the plant

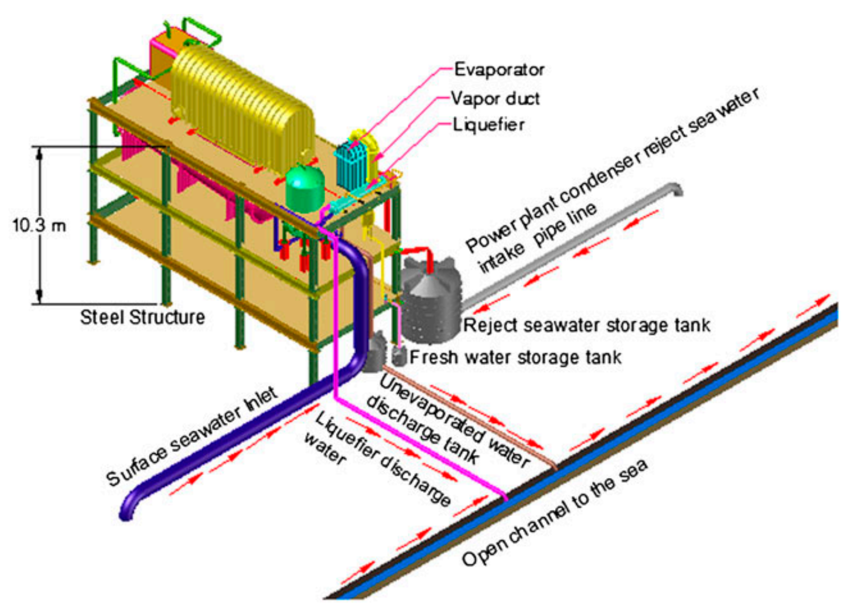

Fig. 2. CAD model of the proposed desalination plant.

operation. Like other conventional thermal desalination systems, waste steam from the process plant can be used for the venting system [7,8]. The steam is thus utilized only in gas ejection and not for preheating the sea water and hence, the spent steam at a relatively low pressure may be reused.

The energy requirement for this desalination system will be minimal, since the head required to feed the evaporator and the latent heat of vaporization is taken up from the feed sea water itself. The energy is required only to pump the surface sea water for condensing the generated water vapour from the evaporator. As the evaporator is located at a height of 10.3 m, it eliminates the need for brine blowdown pumps and thus provides additional economic benefits such as installation and maintenance. As there is a minimum number of motive systems, reliability of the desalination plant increases. The lower operating temperatures which are characteristic of this plant calls for low equipment cost when compared with other high temperature thermal desalination technologies. It also eliminates scaling and other problems associated with high temperature systems.

As the desalination plant is located close to the power plant, the necessary equipment such as sea water pumps, waste steam for venting system, sea water at elevated temperatures and power required to operate the system are readily available. This facilitates the operation of the desalination plant without any major additional capital expenditure. Another specific advantage of this plant is that it does not consist of high-technology elements like membrane filters and fine filters etc. The simplicity of this process also enables control of the quality of the fresh water produced to meet the drinking water or boiler makeup water requirements.

6. Experimental results

The temperature profiles and system process parameters, such as the pressure and temperature differences across the major plant components, are shown in Fig. 4. These measurements show good repeatability and reproducibility during the experimental study. From the figure, it is clear that with the power plant condenser reject thermal gradient of 8.7℃, the difference in temperature between the liquefier and evaporator outlet is 2℃. By allowing 1℃ gradient across evaporator and liquefier, the overall thermal gradient will be 4℃, which forms the minimum gradient with which this proposed desalination plant can operate. Thus, this desalination system can be considered as one having the potential to be driven by using low-quality heat with the least temperature gradient. It can be noticed that the temperature difference across the liquefier is more than that in the evaporator. This can be attributed to the reduced head requirement in the evaporator due to the support gained in lifting feed sea water by the vacuum maintained in the system. The head requirement for the liquefier is higher than that in the evaporator due to the larger pressure drop associated across the liquefier. Any increase in surface sea water flow rate to the liquefier will lead to an increase in the total power consumption.

The ratio of mass flow rate of fresh water generated to the mass flow rate of feed sea water obtained from this plant is 0.5% and hence, the change in

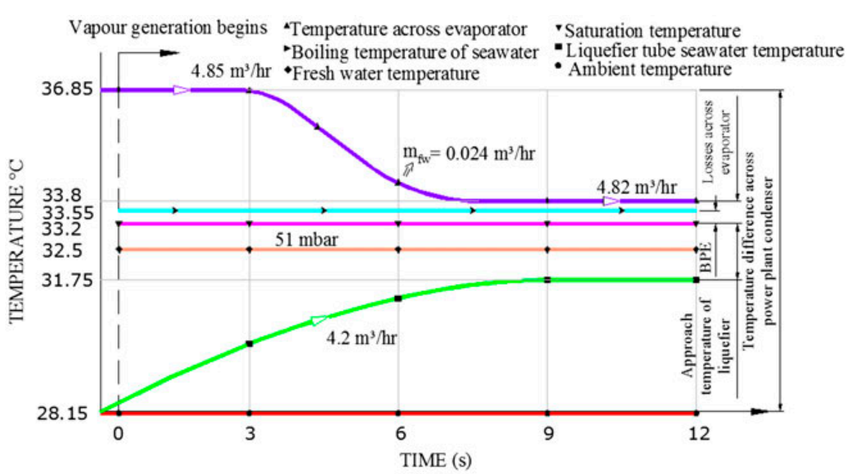

Fig. 4. Temperature profiles across plant components of evaporator and liquefier.

concentration of sea water (salinity levels) discharged from the desalination plant is almost negligible and is closer to that at the intake. The temperature of the un-evaporated discharge sea water is reduced by 3℃, which is lower than the sea water discharge temperature from the power plant condenser to the sea (or cooling tower). This helps in preserving the aquatic environment by means of reduced thermal energy dumped to sea. The salinity of the fresh water is 20 ppm, reduced from the sea water salinity of 35,000 ppm, a quality which is well suited for drinking and for boiler requirements.

In the desalination system tested, the heat in the power plant condenser cooling water is utilized to the maximum. Increased rate of freshwater generation and thereby bringing down the temperature of un-evaporated feed sea water are the two key benefits of this proposed desalination system. A lower evaporator discharge water temperature indicates high-quantity flashing. Since flashing depends on the saturation pressure and its corresponding temperature, a lower thermodynamic loss across the evaporator is desirable.

A temperature difference of 0.6℃ is observed between the un-evaporated discharge water at the bottom of the evaporator and the saturation temperature in the evaporator which is the thermo dynamic loss of the system. This can be attributed to the elevated boiling point due to the dissolved salts in the feed sea water, geometrical shape of the evaporator and the performance of spouts placed in the evaporator.

From the experimental result, it was observed that to generate 1 unit of freshwater, nearly 200 units of sea water was required, which agrees well with the theoretically calculated value. This gives a pumping ratio of 200:1. With a pump efficiency of 85%, density of surface sea water as 1,021 kg/m^3 and 4 m as the head required to overcome the associated frictional losses in the liquefier and the pipe lines, the total energy consumption for the system to pump the sea water to the liquefier can be calculated.

Substituting the corresponding values in Eq. (4), the energy consumption per unit volume is estimated to be 2.62 kWh/m^3 of fresh water produced. This can be compared with the electricity cost of commercial reverse osmosis processes operating at 3.5 kWh/m^3 [9]. These numbers indicate that there is ample opportunity for researchers to look at the probable ways to have a smaller pumping ratio (between the surface sea water and fresh water generated) in order to reduce the cost per unit of fresh water production. Locating the desalination plant adjacent to a warm and cold sea water source will help in decreased pumping head requirements. Higher the waste heat availability at a higher temperature gradient (with the ambient), a smaller pumping ratio can be obtained and a potential exists to generate freshwater with energy consumptions lesser than 1 kWh/m^3. Hence, this proposed desalination technology can be used as a new economical way to generate fresh water. Ongoing research can be aimed to scale up this process to be suitable for high-capacity desalination plants.

The main advantage of the proposed desalination plant is that it can be set up in any new or existing process plant in the world. A desalination plant using this proposed process is being set up in a 1,000 MW power plant in Tamil Nadu, India. The power plant condenser discharges water at 38.2 m^3/s, 12℃ over the ambient temperature and at a positive pressure head of about 2 m. The potential output of this plant would be at least 25,000 m^3/d of fresh water at an estimated energy consumption of 1.57 kWh/m^3. A preliminary investigation to establish 2 modules of 1,000 m^3/d desalination plant is under progress.

7. Experiences gained with the operation of the plant

The successful operation of the experimental plant along with the power plant for a period of more than 15 months has provided valuable experience related to the behaviour of the system. The data collected during full load and part load conditions will serve as feedback for further improvements in the higher capacity desalination plants to be designed. Few of the important observations from the desalination plant operation are described below:

(1) The desalination plant is dependent on the power plant for the condenser reject water and as a result, the availability of the desalination plant is limited by the availability of the thermal power plant.

(2) Initially, the power plant condenser reject water was directly fed to the evaporator and the system operating pressure could not be maintained to the desired level. This is because of the entrapment of a large amount of air along with the feed sea water. Hence, a collection tank is kept at ground level where the power plant condenser reject water is made to flow and the entrapped air is made to bubble out to the ambient. This ensures feed sea water alone flows from the tank to the evaporator.

(3) A sea water pump gland packing leakage was a major problem during the plant operation. As a result, the pump used to produce low suction and hence, the flow rate to the liquefier could

not be maintained for a long period. The nearby structural steel members were heavily corroded due to the sea water spillage in the area through the leak. Apart from the loss of feed sea water from the system and spillage, the pumps used to lose suction head resulting in shut down of the desalination plant. This pump had been replaced with a pump having mechanical seals which improved the desalination plant availability.

(4) Initially, after few days of operation it was found that the surface sea water flow rate to the liquefier was lower than the operational point. This was due to severe blockage of the liquefier tubes due to entry of foreign materials along with the surface sea water. This problem was understood and a SS wire mesh filter was introduced at the entry point of the liquefier which helped in reducing blockages and provided the required sea water flow rate to the liquefier. Periodic cleaning of the filters is mandated.

(5) It is found that the system operating pressure gets automatically adjusted to the summer and winter conditions and to the load on the power plant.

(6) The proposed desalination plant is environment-friendly as it requires no fossil fuels or other external energy for heating/cooling the water. Further, no harmful chemicals or acids are required for the plant operation, since it operates at atmospheric temperature and pressure.

The performance of the proposed desalination plant was found to be satisfactory, and the process has proved to be effective for a reliable production of freshwater without any significant impact on the efficiency of the power plant condenser.

8. Conclusions

A new desalination method has been proposed in this work utilizing low-grade waste heat from the power plant, allowing co-generation of fresh water with electricity. The desalination system analysed in this study used simple concepts to reduce the overall operating power consumption of the plant. An experimental plant has been built and tested in an existing thermal power plant utilizing the condenser reject water to feed the evaporator without using a separate pump. The successful operation of the plant along with the power plant has provided valuable experience and information related to the behaviour of the proposed desalination system during full load and part load conditions. This data serves as a feedback for further improvement for the design of higher capacity desalination plants in the future. As more numbers of new power plant projects are coming up all along the coast line in India, the utilization of this technology can be seriously considered.

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Nomenclature

Symbols

C_p — specific heat of water at certain temperature and pressure, kJ/kg-°C
d — inside diameter of the pipe, m ss
D — droplet diameter, m
E — energy consumed by the pump per unit volume, kWh/m^3
f — friction factor
g — acceleration due to gravity, m/s^2
h — convective heat transfer coefficient at the droplet interface, W/m^2-K
h_{fg} — latent heat of evaporation, kJ/kg
H — head loss due to friction, m
k — loss coefficient
l — length of the pipe, m
$\dot{m}$ — mass flow rate, kg/s
p — pressure, Pa
r — pumping ratio
T — temperature, °C
v — velocity, m/s
z — height above reference, m

Greek

η — pump efficiency, %
ρ — surface sea water density, kg/m^3
σ — Stefan–Boltzmann's constant = 5.6703×10^{-8} W/m^2-K^4
ε — emissivity of the droplet

Subscripts

fw — fresh water
i — inlet
l — liquid
o — outlet
rw — power plant condenser reject water
t — time

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