Desalination and Water Treatment
www.deswater.com

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doi: 10.5004/dwt.2010.1681

15 (2010) 167–171
March

Experiment on stable operating conditions of a dual-effect desalination system

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Received 12 November 2009; Accepted in revised form 24 December 2009

ABSTRACT

In this paper, the stable operating conditions of a dual-effect desalination system were examined by varying the temperatures of the hot water and the feed water. The dual-effect desalination system was made by rearranging a single-stage fresh water generator applied in the ship. Pressures and temperatures were maintained at a steady state. The effect of the temperatures of the feed water and the hot water on fresh water generation rates and the stable operating conditions were explained. The overall heat transfer rates of heat exchangers were obtained from the raw data, and the effect of inlet conditions on the overall heat transfer rates and stable operating condition were described.

Keywords: Dual-effect desalination; Operating condition

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1. Introduction

Desalination is a general term for the process of removing salt from seawater to produce fresh water. Fresh water is defined as water containing less than 1000 mg/L salts or total dissolved solids (TDS) [1]. Thermal desalination systems have been used for hundreds of years to produce fresh water. In the modern world, desalination was first developed for commercial use aboard ships. Distillation, which is the process of using a heat source to desalinate, is used to provide make-up water for steam boilers, as well as to provide drinking water to ocean-bound ships for farther travel [2]. Ships generally adopt one of two types of desalination systems. The first type is a thermal desalination system, while the other is a reverse osmosis (RO) type fresh water generator. The training ship of our university applies both a thermal and an RO desalination system.

The thermal desalination system uses heat from the coolant of the main engine. The thermal desalination system is not easy to operate and to maintain in a vacuum state. The water produced by thermal desalination is more purified than that produced by RO desalination, the demand for thermal desalination systems has been rising accordingly, particularly for cruise ships. The amount of fresh water that is required onboard a cruise ship is particularly high. Assuming that a cruise ship holds 3,300 passengers, with an average consumption of 400 l/d/person, 1,300 tons of fresh water is needed. Today, almost all ships have a single-stage fresh water generator that is able to produce up to 50 t/d. As heat energy is available, the high specific energy consumption of a single-stage evaporator can be accepted, as much as 800 kWh/m^3. A cruise ship requires 43 MW of waste energy, which is much more than is available. The solution to the problem of high specific energy consumption lies in the multi-effect principle. With each effect added, less energy is consumed per unit of fresh water produced. On

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Presented at SeaHERO Academic Workshop on Development and Optimization of SWRO Desalination Systems
Korea University, Seoul, Korea, November 13–14, 2009

ships, 2–6 effects are normally used, for obvious reasons, as a balance needs to be met between the plant capacity and the energy consumption[3].

In the present paper, a single-stage fresh water generator was modified and extended into a dual-effect desalination system. In subsequent experiments, the inlet temperatures of the feed water and hot water were varied, the total fresh water generated, temperatures and pressures of each node were obtained, and the stable operating conditions of the dual-effect desalination system were identified.

2. Experiments

The MED (multi effect desalination) system of the present study is based on a single-stage fresh water generator of a ship. P&ID (pipe and identification) of experimental apparatus and related facilities are shown in Fig. 1. Water is heated by a boiler to 85°C, and induced into the hot water tank. Hot water flows into the desalination system, transfers the heat, and then returns to the tank. A schematic diagram of the dual-effect desalination system is shown in Fig. 2.

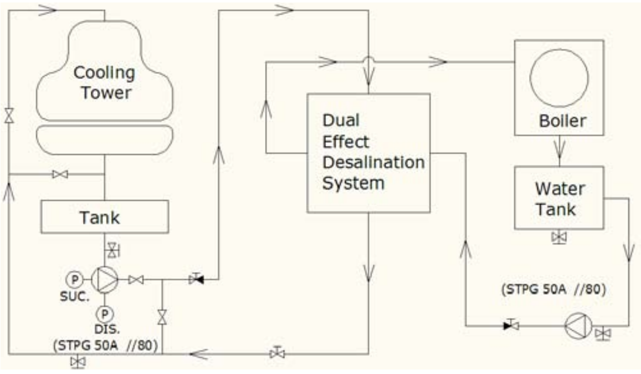

Fig. 1. P & ID of experiment apparatus and related facilities.

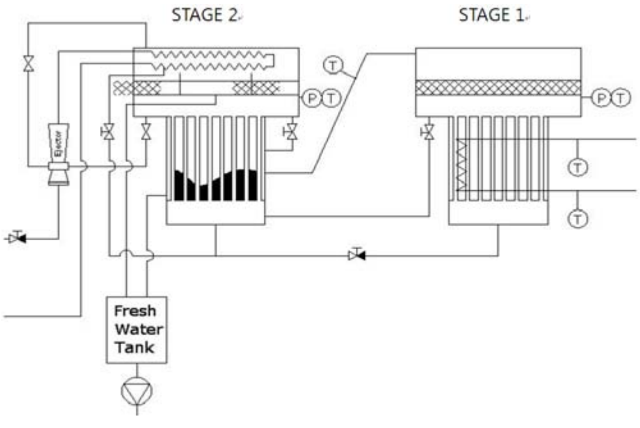

Fig. 2. Schematic diagram of dual-effect desalination.

The main components of the system are a water ejector, a vertical-type evaporator, condenser at each stage and a horizontal-type condenser, and pumps. The water ejector is used to maintain the vacuum state of each stage, and to get rid of non-condensable gas. Heat is supplied to the evaporator of the MED system at the 1st stage. The steam generated in the 1st stage is transferred to the evaporator of the 2nd stage. The steam generated in the 2nd stage is condensed at the main condenser over the evaporator.

Driving water is forced into the water ejector and entrains the non-condensable gas and remaining feed water. After heated in the main condenser, driving water serves as recirculation water and feed water. The pressure is reduced to the vacuum state through an orifice. Feed water is distributed evenly to each stage. The recirculation water returns to a cooling tower and the water cools down.

T-type thermo-couples and pressure transducers and flow meters were calibrated precisely using hot water reservoir and dead weight tester, respectively, and installed at the pipeline between the components. A grove valve at the upstream orifice controlled the total flow rate of feed water, and the flow rate of feed water was controlled by needle valves in the front of each stage. Flow rates of ejector-driving water were measured by a turbine-type flow meter, while flow rates of hot water were measured by a mass flow meter. The water production rates and condensing rates of each condenser were measured by accumulative-type flow meters.

Table 1 shows the experiment conditions of the present study. The temperature of feed water was controlled by a fan, which could be switched on or off. After reaching steady state, one set of experimental data, such as temperature, pressure, etc., was obtained every minute for 30 min, and the 30 sets of data were stored in the computer. Temperatures and pressures were modified using each calibration formula.

The logarithmic mean temperature difference was calculated in the boiling temperature and in the inlet, outlet temperature of each stage. The equation is shown here as Eq. (1) [4].

$$\Delta T_{\text{lmtd}} = \frac{T_i - T_o}{\ln \dfrac{T_i - T_b}{T_o - T_b}} \tag{1}$$

Table 1
Experiment conditions

Description	Values
Flow rate of hot water, l/min	95
Total feed rate, l/h	140
Feed rate of each stage, l/h	70
Temperatures of feed water, °C	22, 24, 26, 28, 30, 32

With the heat transfer rate and the logarithmic mean temperature difference, it is possible to calculate the overall heat transfer coefficient at the 1st stage and 2nd stage with the following Eq. (2).

$$U = \frac{Q}{A_S \Delta T_{\text{lmtd}}} \tag{2}$$

In Eq. (2), A_s is the heat exchange area assumed to be the active tube surface.

3. Results and discussion

Table 2 shows the product water by the desalination process obtained in this experiment. F in Table 2 indicates failure. The product water in parenthesis next to F shows that the temperature and pressure were not in a state of thermodynamic equilibrium and the process was operated unstably. In the case of a failed experiment, it could be observed through a sight glass that the feed water was flooded inside the experiment chamber.

As shown in Table 2, this desalination experiment failed when the temperature of the hot water temperature was below 74°C. In order to examine the operation conditions, feed water temperature was changed, and the temperatures measured at the 1st stage and 2nd stage were indicated in Fig. 3, with their saturation temperatures.

In Fig. 3, the temperature measured by a thermocouple is shown, and its saturation temperature was calculated based on the measured absolute pressure using the thermodynamic relation when saturation status was reached. When the temperature of the hot water was 78°C, the experiment reached steady state and operated stably, and the temperatures measured at 1st and 2nd stage coincided with their saturation temperatures. When the temperature of the hot water was 78°C, the system operated stably at a feed water temperature of 30°C below. When the temperature was above 32°C, thermodynamic equilibrium could not be obtained due to a temperature difference of approximately 3°C–8°C between the measured temperature and saturation temperature. This is because the condensation rate of the steam at the condenser above the upper part of the 2nd stage did not coincide with the evaporation rate feed water at the evaporator of the 2nd stage. When the overall heat transfer coefficients of evaporators in the 1st stage and the 2nd stage are compared, the inconsistency in the amount of evaporation and condensation in the 2nd stage can be explained.

Table 2
Produced water (t/d/effect)

Feed water temperature (°C)	Hot water temperature (°C)				
	74	76	78	80	82
22	F	F (0.413)	1.01	1.09	—
24	F	F (0.322)	1.01	1.12	1.00
26	F	F (0.302)	0.960	1.08	0.878
28	F	F (0.264)	0.768	0.922	0.811
30	F	F (0.216)	0.720	0.883	F (0.662)
32	F	F	F (0.614)	0.749	F (0.653)

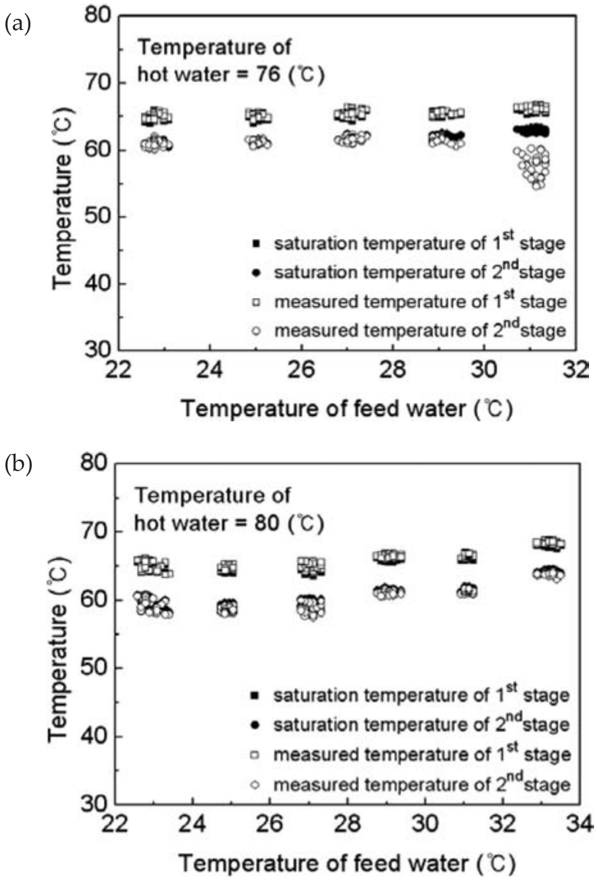

Fig. 3. Variation of temperature at each stage according to the feed water temperature.

Fig. 4 shows the result of overall heat transfer coefficients of evaporators in the 1st stage and 2nd stage. When operated stably, the mechanism of heat transfer is different in the 1st stage and the 2nd stage. In the 1st stage, the feed water flowing inside of the tube was evaporated, and the hot water flowing outside of the tube did not undergo phase change. In the 2nd stage, feed water flowing inside of the evaporator was evaporated, and the steam in the outside of the evaporator was condensed.

The overall heat transfer coefficient of the heat exchanger when the phases-change occurs at both sides of tube is greater than that of the heat exchanger when the phase-change occurs only at one side. In Fig. 4, which compares the overall heat transfer coefficients, the overall heat transfer coefficients are similar to each other in the 1st stage and the 2nd stage. It is believed that feed water flowing inside of the tube in the 2nd stage transmitted

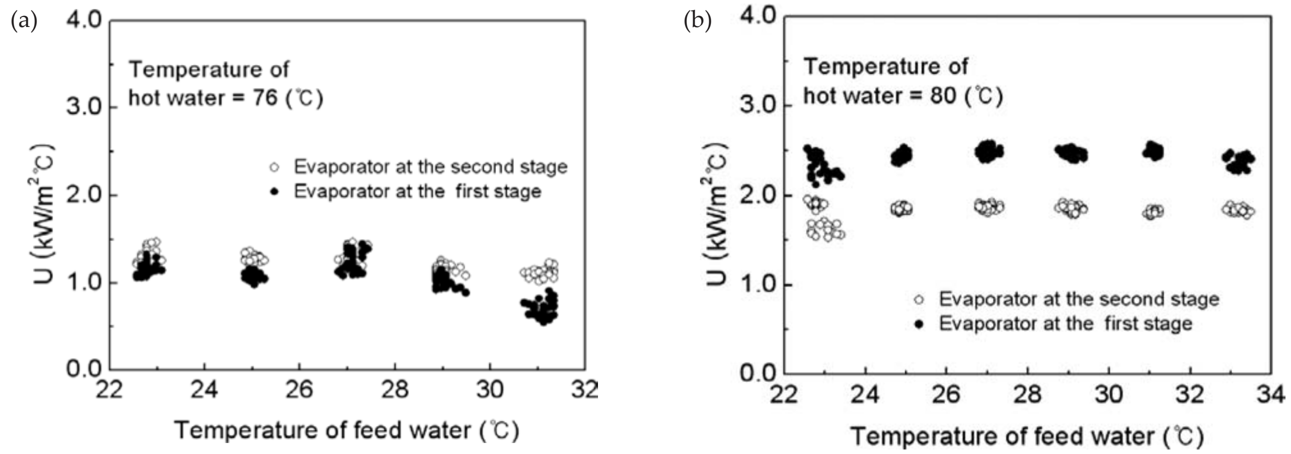

Fig. 4. Variations of overall heat transfer coefficients of each stage by the feed water temperature.

only by the sensible heat instead of phase change, and was evaporated by flashing on the tube end.

The heat amount supplied to the 1st stage in cases of unstable operation and case of stable operation is compared in Fig. 5. When the hot water temperature was 76°C, the desalination system was operated unstably, and if it was compared with the case of a hot water control temperature of 80°C, the heat amount supplied to the 1st stage was reduced by half. If equilibrium between temperature and pressure could not be attained, even with sufficient heat supplied to the desalination system, the system was not stably operated. Table 3 shows the difference between the hot water inlet temperature and the saturation temperature at the 1st stage, focusing on stable operation. It is shown that due to this difference in temperature, the heat of the hot water is transmitted to the seawater desalination system, and that the seawater desalination system is operated stably only when there is a temperature difference of 12°C or more.

Table 3
Temperature difference between hot water and saturation temperature

Feed water temperature(°C)	Hot water temperature (°C)		
	78	80	82
24	14.9	15.7	13.9
26	14.8	15.5	12.7
28	14.5	14.2	12.4
30	12.1	14.2	11.4
32	10.6	12.5	11.7

4. Conclusions

To investigate the safe operation of dual-effect desalination systems, a single-stage fresh water generator was rearranged to form a dual-effect system, and experiments

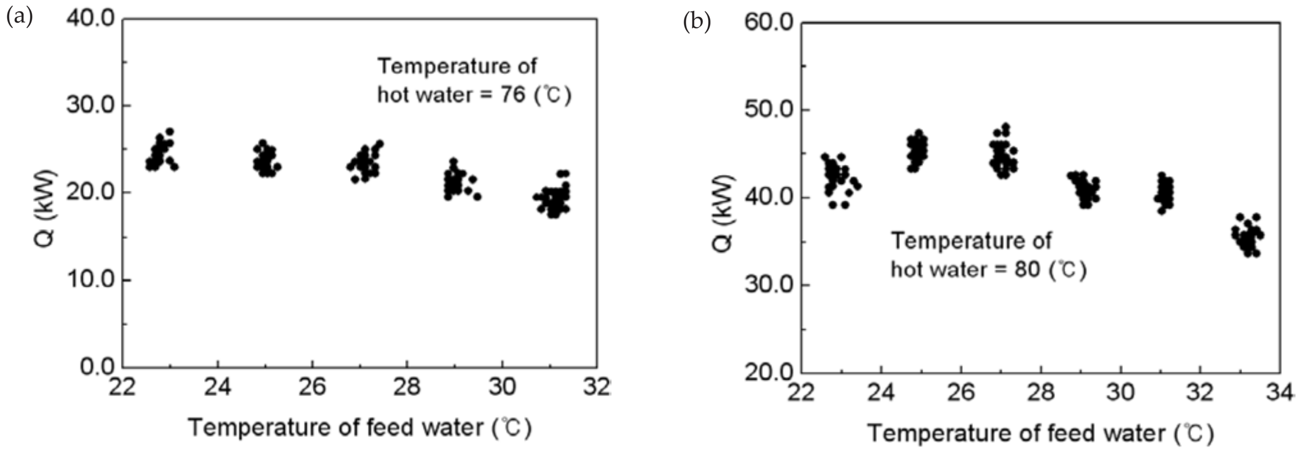

Fig. 5. Variations of heat transfer rates of each stage according to the feed water temperature.

were carried out by varying the temperature of hot water and feed water. Total fresh water generation rates, heat transfer rates from hot water, pressures and temperatures were analyzed. From an analysis of the experimental data, the following conclusions were derived.

Pressures and temperatures of the 1st stage and 2nd stage are highly dependent on the inlet temperatures of the hot water and the feed water. The pressure and temperature at each stage are increased according to the difference between the temperatures of hot and feed water. Stable operation of the sea water desalination system discussed in this study can be attained when there is a balance between the evaporation amount and the condensation amount at the last stage, and the temperature difference between the inlet temperature of hot water and the saturation temperature at the 1st stage should be 12°C or more.

Acknowledgments

This research was supported by a grant (07sea-heroB02-01-04) from the Plant Technology Advancement Program funded by the Ministry of Land, Transport and Maritime Affairs of the Korean government.

Symbols

A_s — Heat transfer area, m^2
Q — Heat transfer rate, kW
T_i — Inlet temperature, °C
T_o — Outlet temperature, °C
T_b — Boiling temperature, °C
ΔT_{lmtd} — Logarithmic mean temperature difference, °C
U — Overall heat transfer coefficient, $kW/m^2{}^\circ C$

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