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Thermodynamic performance of a low temperature multi-effect distillation experimental unit with horizontal-tube falling film evaporation

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ABSTRACT

A five-effect distillation experimental unit was designed and fabricated and the thermodynamic performance was measured and evaluated. The mechanical design and process operation parameters of a low temperature multi-effect distillation experimental unit were optimized. This nit featured horizontal-tube falling film evaporation. Its designed performance was achieved and maintained, and its heat loss was effectively reduced. The variation of temperature and pressure in each evaporator effect and the thermodynamic performance of the unit were tested and analyzed. The results indicated that the measured and calculated vacuum and evaporating pressure in each effect coincided. Water production rate and gained output ratio (GOR) decreased slightly with an increase in flow rate of feed seawater. With an increase in flow rate of heating steam the water production rate linearly increased and GOR slightly increased. The calculated results were found to be fairly close to the experimental observation, which justified the expectation that the analytical model developed for the multi-effect distiller was reliable, and the overall design of the experimental system was correctly done.

Keywords: Horizontal-tube falling film evaporation; Low temperature multi-effect distillation; Thermodynamic performance; Gained output ratio

1. Introduction

Due to the population growth, industrialization and urbanization, a worldwide fresh water shortage has become a major concern. The desalination of seawater may effectively pave the way to resolve water scarcity. The processes of multi-stage flash (MSF), low-temperature multi-effect distillation (LT-MED) and reverse osmosis (RO) are dominating in seawater desalination [1]. MSF is the most popular process of desalination plants and shares almost 50% of the desalination market in the Middle East area. The major practical problem resulting in higher running costs is related to high pressure and temperature in order to gain a satisfactory flashing, and hence,a worthwhile water yield. LT-MED is a kind of desalination technology that uses falling film evaporation over the outer surface of a vertical column of horizontal steam-heated tubes. LT-MED provides higher heat transfer coefficients and operates with smaller liquid inventories than flooded heat exchangers. It also mitigates fouling, the non-condensable gas effect and some other application-specific problems. Recent developments in LT-MED have made this process compete technically and economically with that of MSF and RO [2]. The practical MED demonstration plant built

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by Sidem Company proved that its specific energy consumption, about 5.5 kWh/t [3], is able to compete with that of RO. It is illustrated in Fig. 1 that the technology of worldwide capacity installed by Sidem Company is switching from MSF to MED. RO is operated by electrical power to drive the high-pressure pumps, the pre-treatment processes and other plant auxiliaries. Its power consumption mainly depends on water recovery and the working pressure. As seawater desalination is energy intensive, energy costs are one of the most important factors determining desalination decisions.

Although there are many experimental and theoretical studies concerning LT-MED, most of them are focusing on the heat transfer performance of single tube and tube bundles [4–8]. There appears to be little information in the literature on the thermodynamic performance of the LT-MED system. The objective of this paper is to demonstrate the thermodynamic performance of a low temperature multi-effect distillation experimental unit with horizontal-tube falling film evaporation. A five-effect distillation experimental unit was designed and fabricated. Based on the experimental and theoretical analysis, the variation of temperature and pressure in each evaporator effect and the thermodynamic performance of the unit are explored.

2. Experimental methods and procedures

2.1. Experimental setup

An experimental layout was built under laboratory conditions to carry out experiments on evaporators with falling film horizontal tubes. Parameters need to characterise simultaneously in detail, which include evaporating pressure and temperature in each effect evaporator, the heating steam flow rate and the flow rate of seawater outside tube bundles. A series of tests were conducted at the outset of the project to clarify the experimental requirements. Fig. 2 shows the schematic diagram of the installation in tests. The picture of the experimental setup is shown in Fig. 3. The major setup of this designed desalination unit is outlined below:

(1) A quadrate horizontal-tube falling film evaporator is the major component of the unit. It is a shell-and-tube type heat exchanger. Fig. 4 and Fig. 5 show the details of the evaporator. There are 100 smooth tubes made of aluminium-brass in each evaporator. The tube is 500 mm long, 14 mm in diameter and 1 mm thick. The tube arrangement is regular triangular with a pitch of 21 mm. The cubic shell with 500 mm on each edge is made of 316L stainless steel.

(2) The design of the final condenser adapting to the vacuum condition is based on the two considerations: the vapor from the last effect evaporator capable of being condensed and the non-condensable gas released during the condensation process being convenient to be extracted.

(3) The seawater pre-heater is selected as coil heat exchanger shown in Fig. 6. This kind of pre-heat structure contributes utilizing the un-condensable vapour at the vapour outlet of a horizontal tube to pre-heat the feed seawater. Thus the amount of vapour extracted with non-condensable gas is sharply reduced. In addition, the negative effect of non-condensable gas on the heat

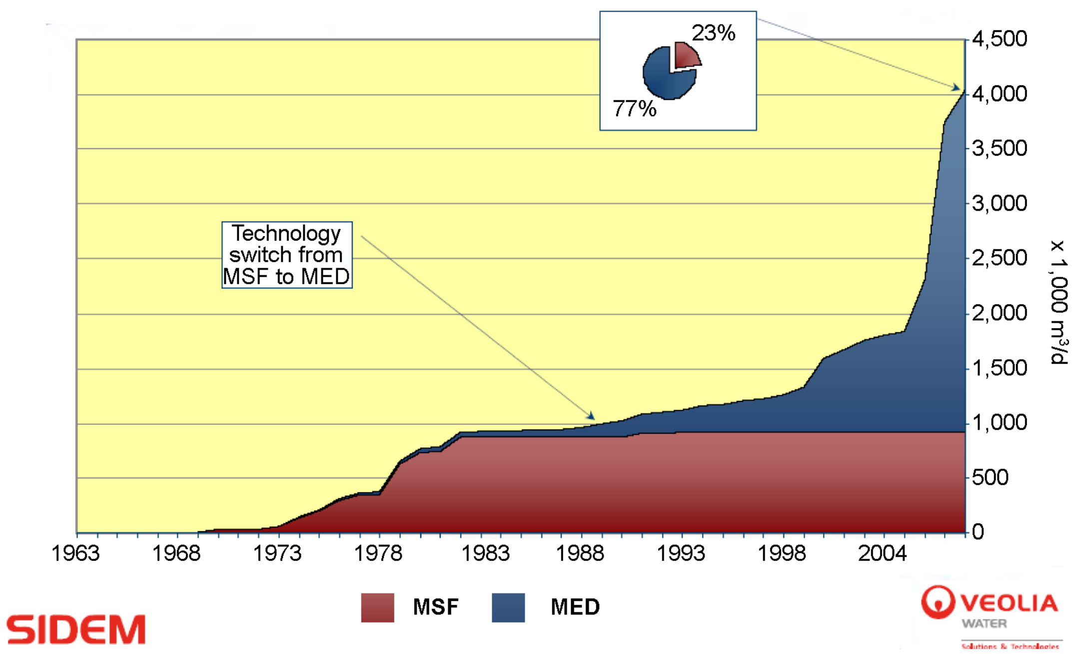

Fig. 1. Comparison of Sidem worldwide capacity installed between MSF and MED.

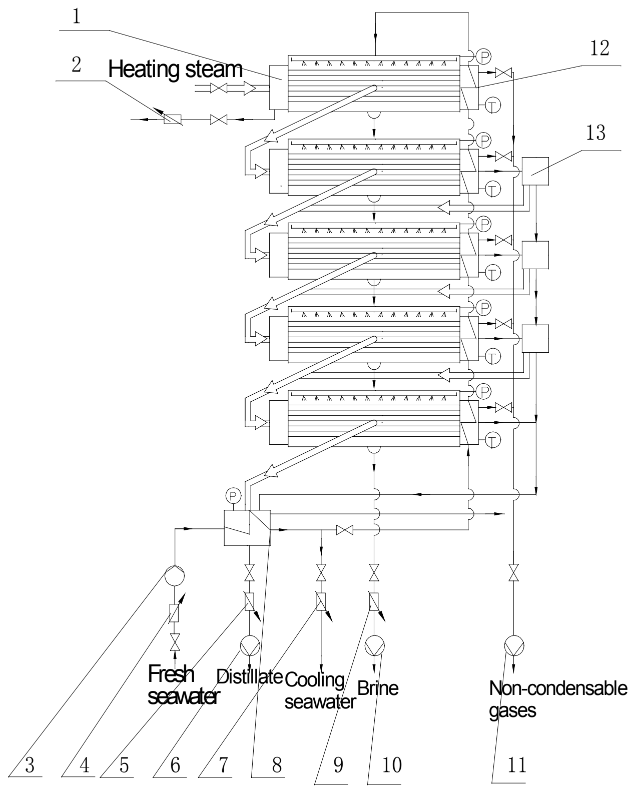

Fig. 2. Schematic diagram of the experimental setup. 1 – Evaporator, 2 – Condensate flowmeter, 3 – Seawater pump; 4 – Seawater flowmeter, 5 – Distillate flowmeter, 6 – Distillate injection pump, 7 – Cooling seawater flowmeter, 8 – Final condenser, 9 – Brine flowmeter, 10 – Brine injection pump, 11 – Vaccuum pump, 12 – Pre-heater, 13 – Flashing box.

Fig. 3. Picture of the experimental setup.

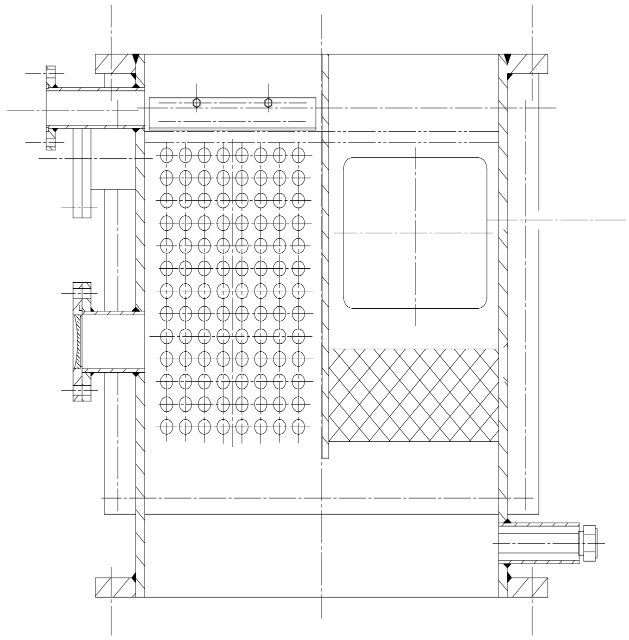

Fig. 4 Structure of evaporator.

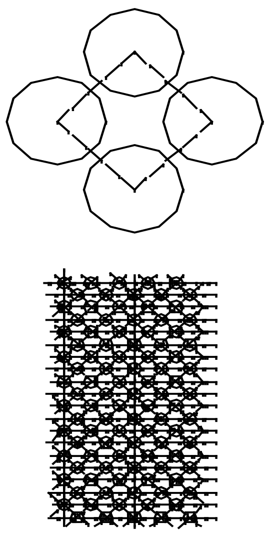

Fig. 5. Layout of tube bundles.

transfer process is limited in the pre-heater instead of the evaporator as the accumulated non-condensable gas is extracted in pre-heater rather than enters the following evaporator.

2.2. Experimental procedure

The evaporator is stacked vertically one on top of the other. Seawater is fed to final condenser 8 in which it flows through tubes, the main duty is to carry off the heat brought into the evaporator. The pre-heated seawater in the final condenser is divided into two parts. The first

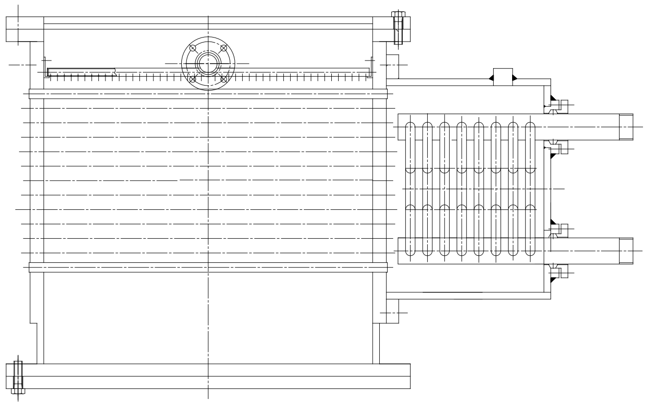

Fig. 6. Structure of pre-heater.

part is allowed to pass successively through pre-heater 12 to increase temperature close to the saturated in the first effect. The second is rejected, known as the cooling seawater. On leaving the topmost pre-heater, the warm feed seawater is sprayed in the form of thin film on the outside of the succeeding rows of tubes arranged horizontally. The concentrated seawater, known as brine, is heated to its saturated temperature before a small portion of it is evaporated. The vapour produced in each effect is condensed in the next effect after being passed through a demister to remove the entrained brine droplet. The rest part of brine is introduced into the next effect. As different effects are stacked vertically, brine cascades downwards by gravity, which can save a substantial pumping power. The processes of spray, evaporation and condensation are repeated in successive effects. The heating steam condenses in the first effect and the condensate returns the boiler feed water after it passes through flowmeter 2. The distilled water is collected at flashing box 13 and the vapour produced by the flashing process together with the vaporized vapour in the evaporator works as heating source for the next effect. The distillate is cooled in the final condenser and pumped to the distillate box by injection pump 6. The brine discharged from the last effect flows to the brine box by injection pump 9. Vacuum pump 11 continuously works to extract non-condensable gas in the final condenser and pre-heaters which are produced during the process of falling film evaporation.

3. Mathematical models

The aim of developing mathematical models is to get a design tool and observe the thermal performance of the experimental unit. The effect of several parameters on thermal performance of the five-effect distillation unit is analyzed by using the mathematical models. Two assumptions are made. The first assumes that the system operates under steady-state conditions. The second assumption is that the heat loss to the ambient is neglected.

The equations describing LT-MED are developed by applying mass balance, energy balance and heat transfer equations to evaporators, flash boxes, pre-heaters and the final condenser simultaneously [9]. The features of LT-MED mathematical models are constant and equal heat transfer area in all effect. The thermodynamic losses from one effect to another are calculated in the mathematical models, which include pressure depression in the demister and vapour transmission lines, boiling point elevation and non-equilibrium allowance inside evaporators and flashing boxes. The model also considers the effect of water temperature and salinity on physical properties of seawater such as density latent heat of evaporation, and the specific volume. Therefore the gained output ratio (GOR) of LT-MED can be expressed as:

$$\mathrm{GOR} = f(D_d, t_0, t_n, X_0, X_n, N) \tag{1}$$

The horizontal tube falling film evaporation includes the processes of internal condensation, external falling film evaporation and conduction of tube wall. The overall heat transfer coefficient K is expressed as

$$K = \frac{1}{\dfrac{1}{h_o} + \dfrac{d_o}{d_i h_i} + \dfrac{1}{2\pi\lambda \ln \dfrac{d_o}{d_i}}} \tag{2}$$

The heat transfer coefficient of external falling film evaporation h_o can be calculated as [10]

$$h_o(\mu^2 / \rho^2 g \lambda^3)^{1/3} = 0.0004\,\mathrm{Re}^{0.2}\, P_r^{0.65} q''^{0.4} \tag{3}$$

The heat transfer coefficient of internal condensation h_i can be given as [11]

$$h_i = \left(1 + \frac{3.8}{\left[\left(\dfrac{1}{\chi} - 1 \right)^{0.8} P_r^{0.4} \right]^{0.95}} \right) \times 0.023 R_e^{0.8} P_r^{0.4} \frac{\lambda_l}{\delta_i} (1-\chi)^{0.8} \tag{4}$$

4. Results and discussion

The designing parameters of the experimental unit are as follows: the heating steam temperature is 70°C, the evaporating temperature in the last effect is 55°C, the temperature of fresh seawater is 20°C, the salinity of fresh seawater has the value of 3.4%, the value of the brine concentration is 2 and the rated capacity of produced water is 300 kg/h.

4.1. Variation of vacuum and evaporating temperature in each effect

The comparison of experimental and calculated vacuum and evaporating temperature in each effect is shown

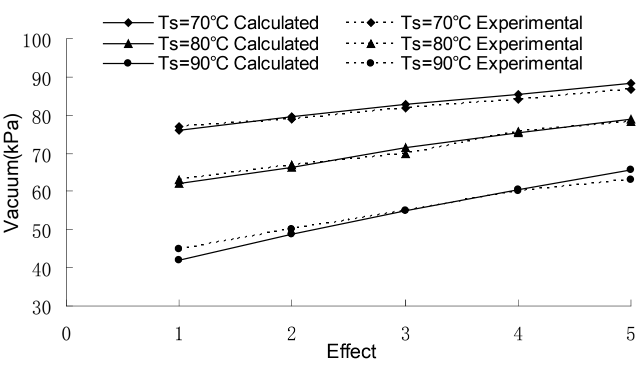

Fig. 7. Variation of experimental and calculated vacuum in each evaporator.

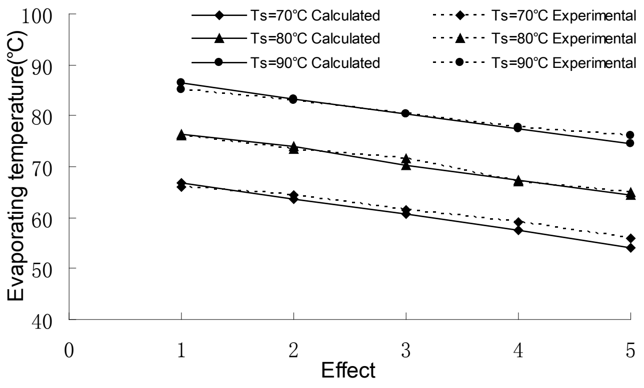

Fig. 8. Variation of experimental and calculated evaporating temperature in each evaporator.

in Fig. 7 and Fig. 8, respectively. The variation tendency of the experimental vacuum and evaporating temperature is almost the same as the calculated values. This justifies the expectation that the overall design contributes to reducing flowing resistance of produced vapour in evaporators, controlling the effect of non-condensable gas on the heat transfer process and decreasing the thermal losses between successive effects. It is also observed that the experimental data is slightly greater than the calculated. The possible reason lies in that the accurate level of the vacuum pressure gauge causes the experimental deviation and the thermal losses caused by non-condensable gas is not taken into account in the mathematical model.

4.2. Influence of flow rate of feed seawater

Fig. 9 shows the effect of flow rate of feed seawater on water production rate and GOR when the other designing parameters keep constant. Water production rate and GOR decreased slightly with an increase in flow rate of feed seawater. On the one hand, the flow rate of feed seawater has little effect on heat transfer coefficient of internal condensation while the increment of flow rate of feed seawater helps to strengthen the convective heat transfer of external falling film evaporation. As a result, the overall heat transfer coefficient slightly increases with an increase in flow rate of feed seawater. On the other hand, with an increase in flow rate of feed seawater, the contact time between the feed seawater and the heating surface of a horizontal tube becomes short. Thus, the water production rate decreases due to a decrease in the quantity of heat absorbed by saturated feed seawater in the falling film evaporation process. At the same time when the flow rate of feed seawater increases, more amount of heat is drained by the discharged brine. The aspect of heat transfer coefficient weights less than the latter aspect on the water production rate and GOR.

In order to eliminate the effect of the heat loss transferring through the juncture of the shells to the ground and through the shell surface to the ambient, the experimental data of water production rate and GOR in Fig. 9 and Fig. 10 are revised. Based on the Stefan–Boltzmann law and experimental correlation of natural-convection heat transfer [13], the thermal loss caused by natural-convection heat transfer and radiation heat transfer is taken into account. It can be seen that the experimental results

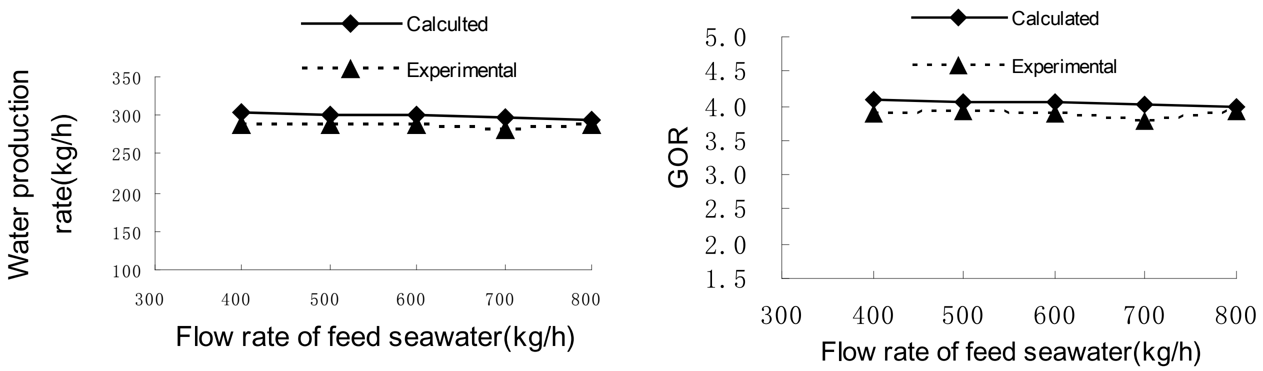

Fig. 9. Effect of flow rate of feed seawater on water production rate and GOR.

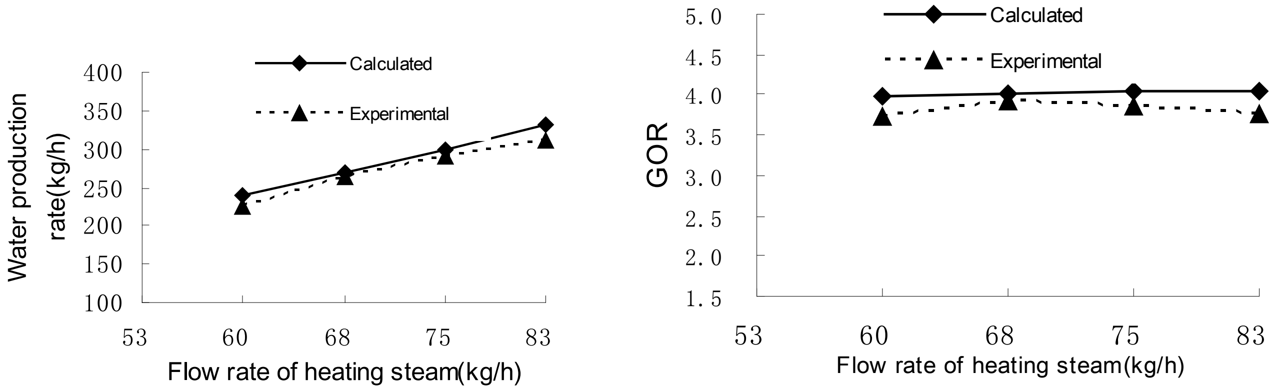

Fig. 10. Effect of heating steam flow rate on water production rate and GOR.

of water production and GOR demonstrate satisfactory agreement with the calculated ones. The comparison between the hypothetical calculation and the outcome make it clear that the analytical model developed for the multi-effect distiller is reliable, and the overall design of the experimental system was correctly done.

4.3. Influence of flow rate of heating steam

The effect of the flow rate of the heating steam on the water production rate and the GOR is shown in Fig. 10. It can be observed in Fig. 10 that with an increase in flow rate of heating steam the water production rate linearly increased and the GOR slightly increased. The possible reasons are as follows: firstly, with an increase in the flow rate of the heating steam, the inlet velocity of internal vapour increases, enhancing the internal condensation. Secondly, with an increase in flow rate of heating steam, more heat energy is supplied to LT-MED system. Under the action of the above factors the water production rate increases with the increment of flow rate of heating steam. As the specific heat consumption of water production in some sort decreases with an increase in flow rate of heating steam [12], the variation tendency of GOR is flat compared with that of water production rate.

5. Conclusions

The unit was designed and built to conduct experiments to evaluate the thermodynamic performances. From the experimental observation and performance data, the following conclusions can be drawn:

The measured vacuum and evaporating pressure in each effect coincided with the calculated values. The water production rate and the gained output ratio (GOR) decreased slightly with an increase in flow rate of the feed seawater. With an increase in flow rate of heating steam, the water production rate linearly increased and the GOR slightly increased. The results of the calculated values are found to be fairly close to the experimental observation, which justifies the expectation that the analytical model developed for the multi-effect distiller is reliable, and the overall design of the experimental system is correctly done.

Symbols

d_o	—	Outside diameter, m
d_i	—	Inside diameter, m
D_d	—	Flow rate of distillate, kg/s
g	—	Gravity acceleration, m/s^2
h_0	—	Heat transfer coefficient of external falling film evaporation, W/m^2·K
h_i	—	Heat transfer coefficient of internal condensation, W/m^2·K
k	—	Overall heat transfer coefficient, W/m^2·K
N	—	Number of effects
Pr	—	Prandtl number
q''	—	Heat flux, W/m^2
Re	—	Reynolds number
t_0	—	Heating steam temperature, °C
t_n	—	Saturated steam temperature in the last effect, °C
X_0	—	Intake seawater salinity
X_n	—	Rejected brine salinity
λ	—	Coefficient of heat conductivity of tube wall, W/m·K
μ	—	Dynamic viscosity, kg/m·s
χ	—	Mass percentage of internal steam

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