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A new multi-effect desalination system with heat pipes by falling film evaporation in the vacuum

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ABSTRACT

An innovative multi-effect heat pipes desalination system with falling film evaporation is presented, in which the evaporation and the condensation is in the negative pressure. The system makes use of the heat pipe to insulate heat source and cold source, has high heat transfer efficiency and effectively avoids producing salt on the surface of pipe because the system operates in the negative pressure and the seawater saturated temperature of evaporation or condensation is at 40–70°C. The multiple effect desalination system can use low-quality energy sources such as discharged smoke heat, cooling water, solar energy, and etc. The system can utilize the latent heat properly in which on one side the heat pipe is heated by condensing vapor generated in the previous stage, whereas on the other side, seawater is distributed by a falling film to evaporate. In conditions of similar water yield, compared with a nine-stage desalination system, MED with heat pipes has small heat transfer area which is reduced by 25%. It indicates that heat pipe multi-effect desalination technology has a good potential for practical applications.

Keywords: Desalination; Heat pipe; Falling film; Evaporation

1. Introduction

Water shortage is an important issue in many places of the world. Lack of water in remote islands or on the ships is especially evident. One of the most promising solutions to the problem is seawater desalination. Now the main desalination methods are distillation driven by heat, reverse osmosis driven by pressure and electrodialysis driven by electricity [1]. Heat-driven processes can use steam, waste heat, solar energy, etc. In the past fifty years, desalination technologies such as MED, MSF and RO have been utilized widely in the world [2]. Toady, facing energy resources supply emergency, desalination systems are being developed from the point of view of efficient performance and the use of low grade or waste heat. In particular, the new desalination system using solar energy, waste heat and etc. has become an important issue of study.

This paper presents a new approach to desalination which is falling film evaporation desalination with heat pipes [3]. A falling film on one side of the heat pipe evaporates in the negative pressure and the other side of heat pipe is heated so that the heat resource may be low quality heat, such as solar energy, gas waste heat and cooling water heat. The steam from the previous effect or stage is a heat resource to drive the next effect or stage to evaporate, simultaneously, the steam is cooled to produce

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water. In the article, the operation process of the heat pipe desalination system is presented and mathematical model of the system is constructed to analyze the thermodynamic performance of the system.

2. System configuration and operation principle

The scheme of the multi-effect heat pipe desalination system is shown in Fig. 1. One side of heat pipes was heated by heat resource, the heat was transferred by heat pipe to the other side to evaporate on which seawater was spray. The steam produced from this effect heats the next spray seawater to evaporate and it is cooled to become freshwater. Every effect operates in the given negative pressure to ensure low evaporation temperature and to keep the temperature difference in every effect. Thus, the evaporation process and condensation process progress respectively. This gives a new heat transfer approach which is not like the former MED system where the steam is cooled in the pipes. It could make the system structure to dispose conveniently. The desalination system can utilize all kinds of energy sources such as discharged smoke heat, cooling water, solar energy, etc.

3. Mathematical model

One effect of the multi-effect heat pipe desalination system is studied. The mass balance equation is:

$$G_{i-1} = G_i + W_i \tag{1}$$

In the formula, G_{i-1} is inlet seawater flow of the effect, kg/H; W_i is steam produced from this effect, kg/H; G_i is outlet seawater flow of the effect, kg/H.

Salt balance equation is:

$$G_i \cdot C_i = G_{i-1} \cdot C_{i-1} \tag{2}$$

In the formula, C_i and C_{i-1} are outlet and inlet brine consistency, %.

Energy balance equation is:

$$W_i \cdot r_i = \left[D_{i-1} \cdot r_{i-1} + G_{i-1} \cdot C_{p(i-1)} \cdot (T_{i-1} - T_i)\right] \cdot \eta \tag{3}$$

In the formula, r_i is the steam latent heat of the effect, J/kg, η is the thermal efficiency of every effect.

The brine boiling point of the effect is:

$$T_i = T_i + \mathrm{BPE}(C_i, T_i) \tag{4}$$

In the formula, BPE is seawater boiling point [4] which is:

$$\begin{aligned} &\mathrm{BPE}\ (C,T) = \\ &(5.28764 \times 10^{-2} + 8.2603 \times 10^{-4} T - 3.15082 \times 10^{-8} T^2) C \\ &+ (3.20553 \times 10^{-3} - 1.44367 \times 10^{-5} T - 1.84416 \times 10^{-7} T^2) C^2 \end{aligned}$$

The steam temperature of the effect is:

$$J_{i-1} = T_{i-1} - \mathrm{BPE}\ (C_{i-1}, T_{i-1}) \tag{5}$$

The difference in temperature of the effect is:

$$S_i = J_{i-1} - T_i \tag{6}$$

The consuming quality for pre-heater is:

$$W_{0i} = \frac{G_0 \cdot C_{pi} \cdot (T_i - T_{i+1})}{r_i} \tag{7}$$

The heat transfer formula is:

$$\begin{aligned} &D_{i-1} \times r_{i-1} + C_{p(i-1)} \times G_{i-1} \times (T_{i-1} - T_i) \\ &= A_i \times k_i \times (T_{i-1} - T_i) \end{aligned} \tag{8}$$

In Eq. (8) A_i is the falling film evaporation area of heat pipe; k_i is the total heat transfer coefficient of the effect

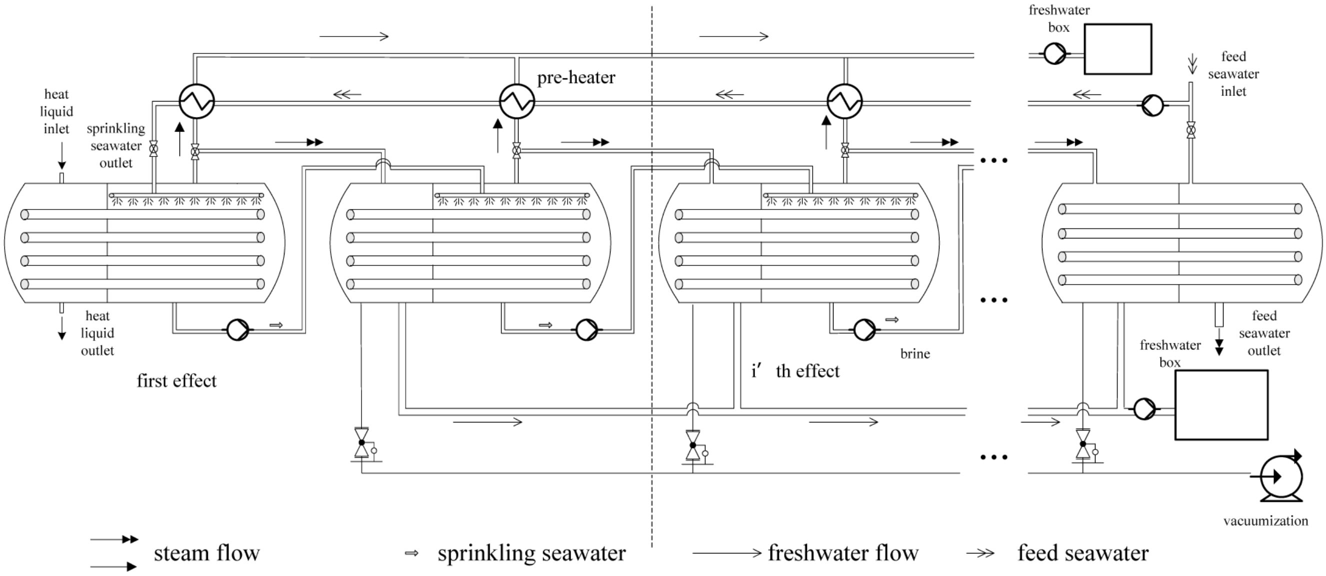

Fig. 1 Scheme of a multi-effect heat pipe desalination system.

which is base of the falling film evaporation area of heat pipe.

$$k_i = \frac{1}{\frac{1}{h_{1i}} + \frac{d_i \cdot \ln(\frac{d_i}{d_i - \delta_i})}{2\lambda_i} + \frac{l_{1i} \cdot d \cdot \ln(\frac{d_i}{d_i - \delta_i})}{2\lambda_i \cdot l_{2i}} + \frac{l_{1i}}{h_{2i} \cdot l_{2i}} + R_{fi}} \quad (9)$$

In Eq. (9) l_1 is the heated length of the heat pipe; l_2 is the discharged length of the heat pipe; h_{1i} is the heated heat transfer coefficient of the heat pipe [3,5] which is:

$$h_{1i} = \begin{cases} C\,\mathrm{Re}^n\,\mathrm{Pr}^{1/3} & (a) \\ 0.541\left[\frac{gr\rho_l^2\lambda_l^3}{\eta_l(t_s - t_w)}\right]^{1/4} \cdot \mathrm{Pr}_f^{0.961} \cdot (\frac{p_v}{p_b})^{-0.02} & (b) \end{cases} \quad (10)$$

h_{2i} is the discharged heat transfer coefficient of the heat pipe [3,5] which is:

$$h_{2i} = \begin{cases} \lambda / \left[\frac{ax\mu^{\frac{2}{3}}}{8(\rho_l - \rho_v)^{\frac{1}{3}} g^{\frac{2}{3}} (3m)^{\frac{1}{3}} \sin^{\frac{2}{3}}(\frac{x}{R})}\right]^{\frac{1}{3}} & (a) \\ C\,\mathrm{Re}^n\,\mathrm{Pr}^{1/3} & (b) \end{cases} \quad (11)$$

The heated steam quality for heated the next effect is:

$$D_i = W_i - W_{0i} \quad (12)$$

4. Six-effect heat pipe desalination system

A six-effect falling film evaporation desalination system with heat pipes was proposed. The devised target parameters are as follows:

- water-production capacity $W = 800$ kg/h
- inlet seawater consistency $C_0 = 3.45\%$
- feed seawater temperature 40°C
- heat resource inlet temperature 80°C
- top temperature of seawater $t_1 = 65°C$
- seawater temperature of last effect $t_{out} = 46°C$
- thermal efficiency of every effect $\eta = 98\%$ (it was initialized at first then modified with the calculating progress)
- seawater concentrate rate $C_R = 1.8$

Considering the above targets, isothermal design principle was introduced to create the desalination system with heat pipes. The temperature difference between the effects Δt was 3.8°C. By the isothermal distributing rule, the number of effects was $N = [(t_1 - t_{out})/\Delta t] + 1 = 6$.

Then and the water yields rater was approximately determined as $\varepsilon = 0.8 \times N = 4.8$.

Based on the mathematical model of the system, the thermal parameters of every effect are shown in Table 1.

In design calculation, the heat pipe diameter was 25 mm and the length of heat pipe was 1500 mm. The flow density was 0.145 kg/m·s. The heat transfer coefficient of every effect is shown in Table 2. The heated segment area of the heat pipe was enhanced by 15% and the discharged segment area of heat pipe was enhanced by 10%.

Based on the flow density, sprinkle seawater quality and the length of the heat pipe in falling film evaporation, the heat pipe number of every effect could be determined:

$$n = \frac{G_i}{3600 \times \Gamma \times L_{\text{condensation}}} \quad (13)$$

In above formula, n is the heat pipes number.

In conditions of similar water yield, we compared heat pipe desalination system with a nine stage MED desalination system [6]. The comparative results are shown in Table 3. From Table 3, the freshwater yield rate vs. total area of the HTMED (heat tube multi-effect evaporation desalination system) was enhanced by about 30% as compared to MED. This shows that the HTMED system has good heat transfer effect, less heat transfer area in the same conditions and good industrial application.

5. Thermodynamic performance analysis

In the following, the thermodynamic performance of

Table 1
Effect parameters of heat pipe desalination system

Effect number	T_i (°C)	P_i (MPa)	C_i (%)	W_{0i} (kg/h)	BPE$_i$ (°C)	J_i (°C)	S_i (°C)	W_i (kg/h)	G_i (kg/h)	D_i (kg/h)
0		0.1013	3.45			75			1333	166.70
1	65.00	0.0250	3.65	10.05	0.435	65.5	10.00	169.6	1005.69	156.82
2	61.23	0.0222	3.88	9.91	0.491	61.7	4.27	168.8	865.28	150.03
3	57.45	0.0179	4.43	9.82	0.582	57.9	4.25	161.6	737.01	143.15
4	53.65	0.0148	5.18	9.73	0.665	54.1	4.25	151.8	623.28	136.88
5	49.85	0.0126	6.18	9.69	0.753	50.3	4.25	142.6	501.05	128.96
6	46.06	0.0101				46.1	4.24			
Water ΣW_i								794.4		

Table 2
Heat transfer coefficient of every effect

Effect number	Heat transfer coefficient of the heat pipe (W/m^2·°C)	Heated area of the heat pipe (m^2)	Discharged heat transfer coefficient of the heat pipe (W/m^2·°C)	Discharged area of the heat pipe (m^2)	Length/total length of heat pipe (%)	Heat pipe disposal (row×line)
1	14578	3.71	10985	7.51	33.07	32×3
2	10738	6.82	10735	7.38	48.03	41×3
3	11053	6.35	10582	7.23	46.76	39×3
4	11410	5.81	10382	6.92	45.64	36×3
5	12268	5.58	10169	6.80	45.08	35×3
6	12951	4.77	24881	3.18	60.00	23×3

Table 3
Performance parameters of HTMED and LTED

Name	Six-effect HTMED	Nine stage MED
Seawater concentrate rate	1.79	1.5
Seawater cycle quality, t/d	32.2	30
Dense brine quality, t/d	12.0	20
Seawater consistency, %	3.45	3.6
Brine boiling point, °C	65	65
Evaporation temperature of last effect, °C	46.06	39
Heat resource inlet temperature, °C	80	78
Heat resource temperature drop, °C	10	10
Effect number or stage number	6	9
Heat transfer area, m^2	72.06	50.18
Water production rate vs. total area, kg/(m^2·d)	264.58	199.28

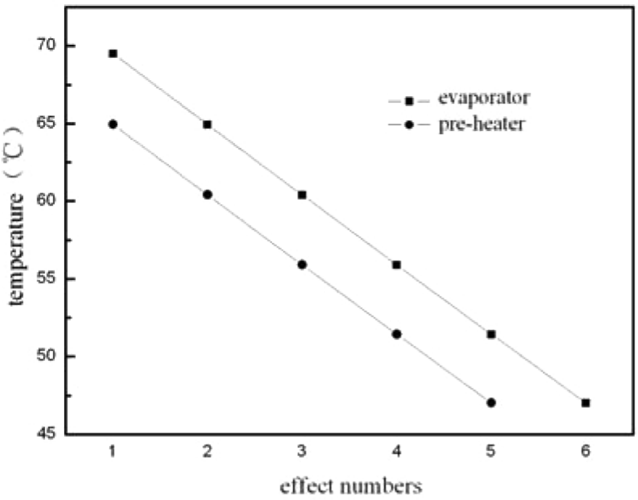

Fig. 2. Distributing rules of brine temperature in every effect of evaporator and pre-heater.

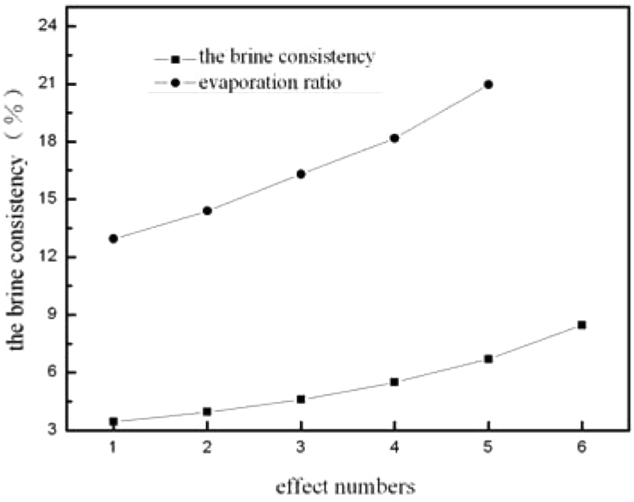

Fig. 3. Variation of brine consistency and evaporation ratio in every effect.

the six effect heat pipe desalination system was analyzed. Fig. 2 shows the distributing rules of brine temperature in every effect evaporator and pre-heater. The brine consistency in every effect is shown in Fig. 3. From Fig. 3, the brine consistency increased with the effect number increasing. According to Figs. 2 and 3, the last effect, in which the brine temperature is lowest, is the place in which the brine consistency is highest, and the first effect, in which the brine temperature is the highest, is the place in which the brine consistency is the lowest.

When the other parameters are not changed, the effect of top temperature of seawater and evaporation effect numbers on the water yields rate are shown in Fig. 4. From Fig. 4 it can be seen that water yield rate did not change with top temperature of seawater and the water yield rate increased with evaporation effect number increasing.

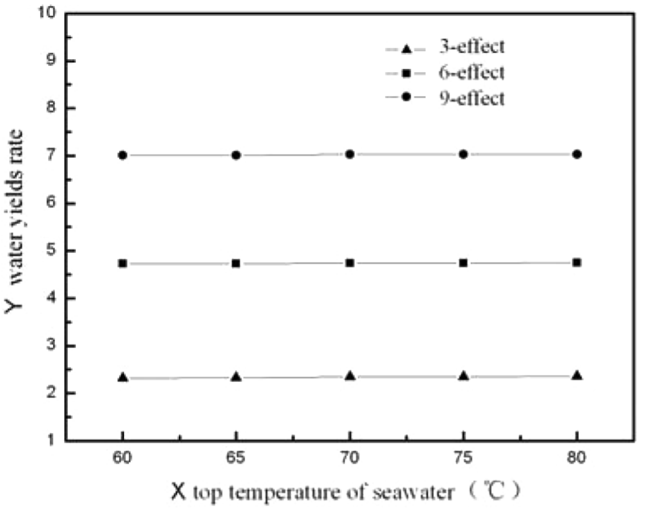

Fig. 4. Variation of water yields rate with top temperature of seawater and evaporation effect number.

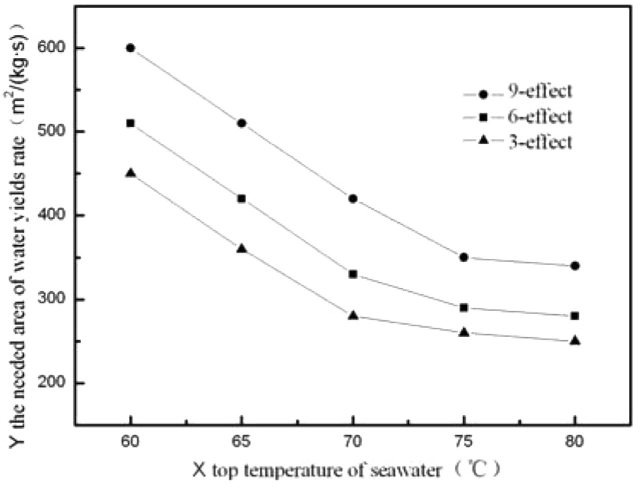

Fig. 5. Variation of needed area of water yield rate with top temperature of seawater and evaporation effect number.

When the other parameters are not changed, the effect of top temperature of seawater and evaporation effect numbers on the needed area of water yields rate are shown in Fig. 5. With the top temperature of seawater increasing, the needed area of water yield rate reduces. On the contrary, the needed area increased with the evaporation effect number increasing.

6. Conclusion

The multi-effect heat pipe desalination system is a new desalination method. The mathematical model of the system is presented. Based on the model, a six-effect heat pipe desalination system was designed and the thermodynamic parameters were obtained. By the thermodynamic performance analysis and comparison of the heat pipe desalination system with a nine stage MED desalination system [6], the following results were obtained:

1. The multi-effect heat pipe desalination system has a high heat transfer efficiency. It can reduce the needed heat transfer area, thus reducing the original cost of desalination system construction.
2. Water production rate vs. total area of HTMED was higher than that of the MED desalination system.
3. For the configuration disposal of desalination system, the multiple-effect heat pipe desalination system can easily use low quality energy sources such as discharged smoke heat, cooling water, solar energy, etc.

The HTMED system has a good application potential. It made the configuration of desalination system to be disposed easily. In conditions of similar water yield, it has the advantage of less heat transfer area and good water yield capacity.

Acknowledgment

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