# Mass Transfer Analysis of Diffusion-gap Distillation

**P Wang*, B C Yu, S M Xu and L Xu**

Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, School of Energy and Power Engineering, Dalian University of Technology, Dalian 116024, China

Corresponding author and e-mail: P Wang, wp2006@dlut.edu.cn

**Abstract.** Diffusion-Gap Distillation is a new type of thermal seawater desalination process, the operation and structure are very simple. A physical model of single-stage Diffusion-Gap desalination plant was established using MATLAB based on the theory of conservation of heat and mass. The sensitivity of hot material temperature, cold material temperature and flow rate were analysed. Computational results have an important influence in the design of the model and the setting of operating conditions.

## 1. Introduction

There are many methods for seawater desalination, they can be divided into two categories according to the principle of brine separation [1]. One is the thermal method, the separation is achieved by heating or cooling to promote the mass transfer of the vapor phase, including: MED, MSF, VC, freezing-melting, HDH etc. The other is the membrane method, by using a porous membrane to block the passage of brine and produce fresh water, including RO and ED. Diffusion-Gap Distillation (DGD) is a separation method developed from the air-gap membrane distillation, it can be used widely, such as seawater desalination [2], treatment of high saltwater [3], recycle of waste water [4, 5] and so on. In the low-grade thermal power plant studied by G Han [6] and L Rui [7], membrane distillation separation takes advantage of temperature difference to produce fresh water and provides power for the cycle, the MD process can be completely replaced by DGD. The liquid desiccant air conditioning system (LDAC) studied by Andrew Lowenstein [8, 9] uses the falling film of desiccant on the plate to absorb the water vapor in the air and the desiccant diluted regenerated by the falling film evaporation process, It is essentially the same as the DGD separation process. In this paper, mass and heat transfer simulation of Diffusion-Gap Distillation process was carried out according to the principle of energy conservation. The influence of feed and coolant temperature and mass flux on freshwater yield was analyzed.

## 2. Mathematical model

### 2.1. Physical model

Figure 1 shows a physical model of a Diffusion-Gap Distillation device. The Diffusion-Gap Distillation device is mainly composed of two plates, they are close to each other and are placed parallel. One of the plates is a layer of porous media and constitutes an evaporator. The other has a

Wang, P., Yu, B., Xu, S. and Xu, L.
Mass Transfer Analysis of Diffusion-gap Distillation.
In *Proceedings of the International Workshop on Environmental Management, Science and Engineering (IWEMSE 2018)*, pages 119-124
ISBN: 978-989-758-344-5

flow channel inside it, which is called condenser. During the operation of the device, cold water flows from the bottom of the condenser and flows upward along the flow channel. After flowing out from the top of the condenser, the solution is heated by an external heat source. It then flows into the evaporator porous medium and flows from top to bottom. When the solution flows in the evaporator, the water vapor in the air layer of the evaporator and the condenser is saturated. Since the temperature for evaporator is higher than the condenser, the vapor pressure on the evaporator is greater than on the condenser. Water vapor is driven by this pressure difference to evaporated from the evaporator and diffused through the air gap to condense on the condenser to produce fresh water.

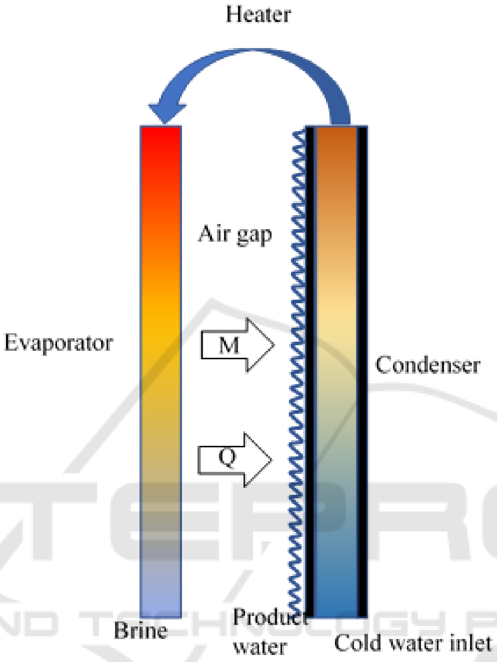

**Figure 1.** Physical model of diffusion-gap distillation device.

### 2.2. *Mass transfer simulation*

Take an element of length dx at the x position as the study object. Assuming the temperature and mass flux at the upper inlet of the evaporator and condenser have been known. Due to the temperature difference, Water vapor diffuse form left to right driven by the temperature-induced vapor pressure difference. According to Fick's law of diffusion, the amount of diffusion that is the change in flow rate on the evaporator is [10]:

$$\frac{dm_f(x)}{dx}=\frac{A}{L}\frac{DP}{RYT_m(x)}\ln(\frac{P-P_p(T_p(x))}{P-P_f(T_f(x))}) \qquad (1)$$

Where $A$ is the total area of the evaporator, L is the length of the model, $D$ is the mass diffusivity between the air and water vapor, $R$ is the universal gas constant, $Y$ is the air gap width, $P$ is the total pressure, $P_p(T_p(x))$ is the vapor pressure according to the temperature of the Condensate film $T_p(x)$, $P_f(T_f(x))$ is the vapor pressure according to the temperature of the evaporator surface $T_f(x)$. The partial pressure of water vapor is a function of temperature and solute concentration and can be calculated by empirical formula. $T_m(x)$ is the average temperature of the evaporator and the condenser.

The temperature of the hot fluid in the evaporator decreases due to water evaporation. According to the conservation of energy, we can get the equation (2). In the formula, $m_f(x)$ is the flow rate of hot material, $h_f(c(x),T_f(x))$ is the specific enthalpy of sodium chloride solution at c(x) concentration and $T_f(x)$ temperature, $h_{vap}(T_f(x))$ is the latent heat of $T_f(x)$ solution.

$$d[m_p(x)h_p(T_p(x))] = dm_p(x)\cdot h_{vap}(T_p(x)) \tag{2}$$

It is the same to the changes in flow rate and temperature on the evaporator, the increase of condensate flow rate and temperature of the condenser can be calculated by equation (3) and (4).

$$\frac{dm_p(x)}{dx} = \frac{A}{L}\frac{DP}{RYT_m(x)}\ln\left(\frac{P-P_p(T_p(x))}{P-P_f(T_f(x))}\right) \tag{3}$$

$$d[m_p(x)h_p(T_p(x))] = dm_p(x)\cdot h_{vap}(T_p(x)) \tag{4}$$

Since the calculation process is to solve each small element from top to bottom, the condition must be known is the upper temperature of the condenser. The actual situation has been known is the bottom inlet temperature of the condenser. An upper temperature of the condenser is assumed during the calculation. The calculated condenser inlet temperature is compared with the actual set temperature. Calculation is completed until the calculation result is equal to the set value. The cycle diagram of the entire calculation process is shown in Figure 2.

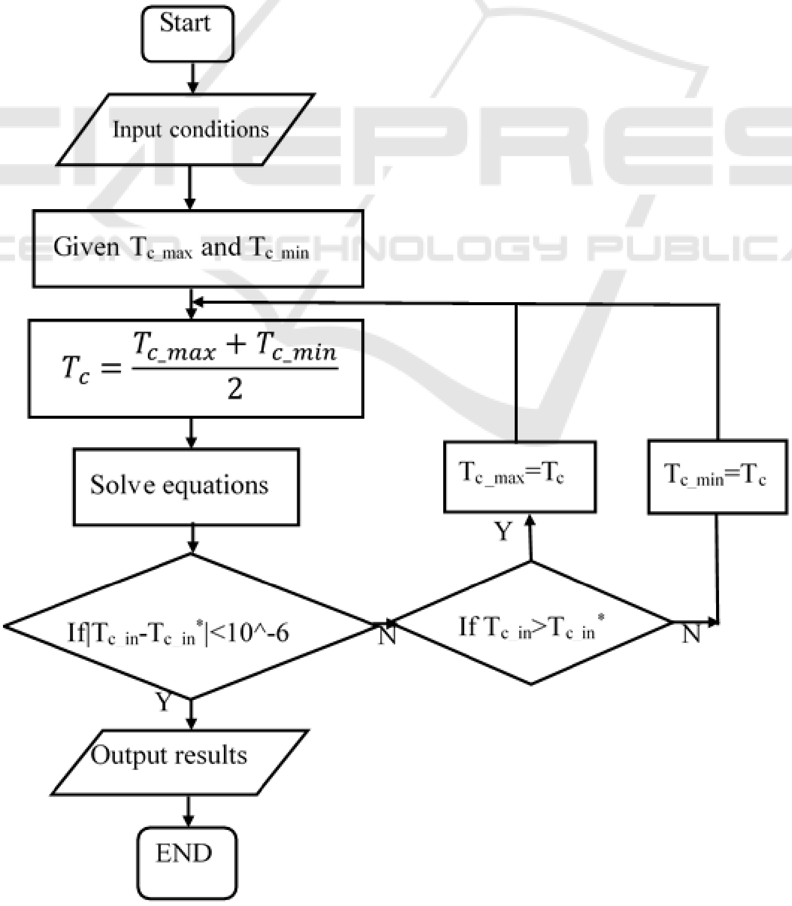

**Figure 2.** Calculation algorithm of the of the entire calculation process.

### *2.3. Model rationality analysis*

The model of flow rate 0.01kg/s, hot material temperature 363.15K, cold material temperature 293.15K, concentration 0.62 mol/kg is simulated with different grid number. The result is shown in Figure 3. When the number of grids is greater than 200, the result curve tends to be flat, the increase in the number of grids has little effect on the calculation results. So, the simulation is done with a grid length of 0.002m.

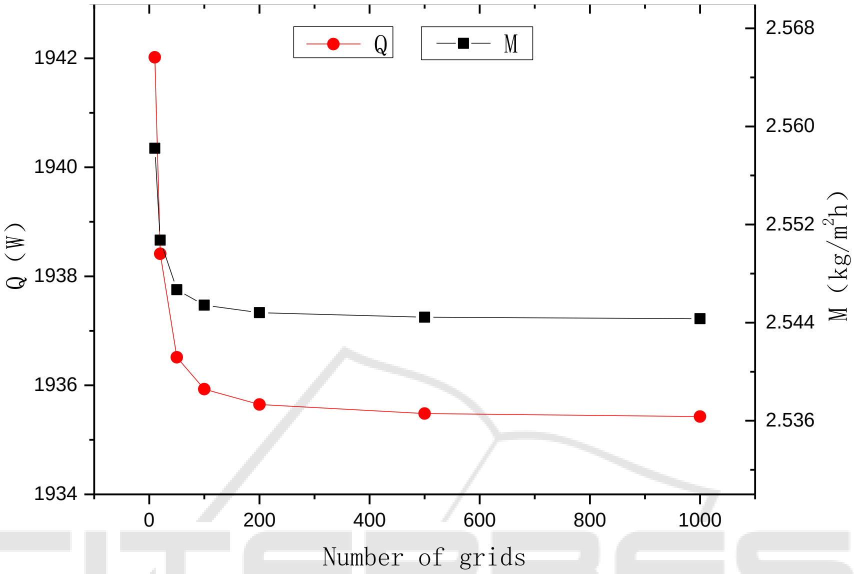

**Figure 3.** The effect of the number of grids on the calculation results.

## 3. Simulation results and analysis

### *3.1. Effect of feed temperature*

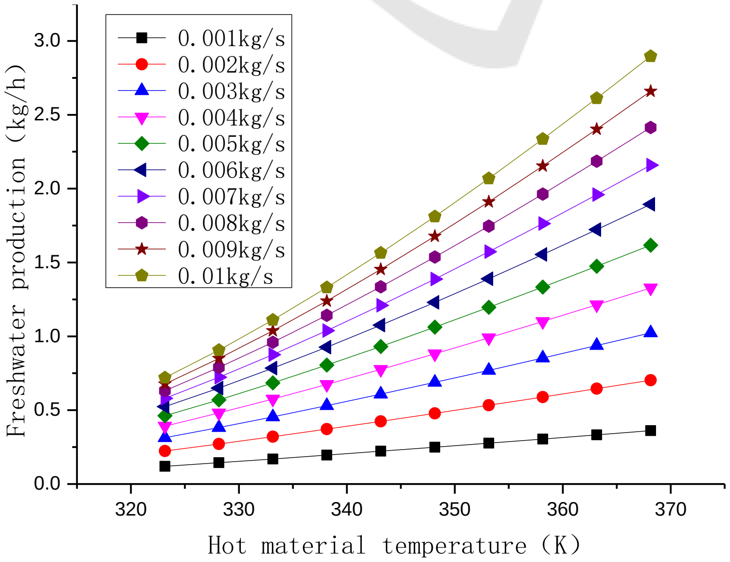

**Figure 4.** Effect of hot feed temperature and flow rate on freshwater production.

As can be seen from Figure 4, when the temperature of the cold material is fixed at 20°C, the output of freshwater increases as the temperature of the hot material rises. And in the case of relatively large flow, the diffusion flux increases roughly exponentially. The driving force of the steam diffusion is the vapor pressure difference between the evaporator and the condenser, and the saturated water vapour partial pressure is related to temperature. When the inlet temperature of the cold material is constant, increasing the temperature of the hot material corresponds to an increase in the driving force for vapour diffusion, so the amount of condensation increases with the increase in the temperature of the hot material.

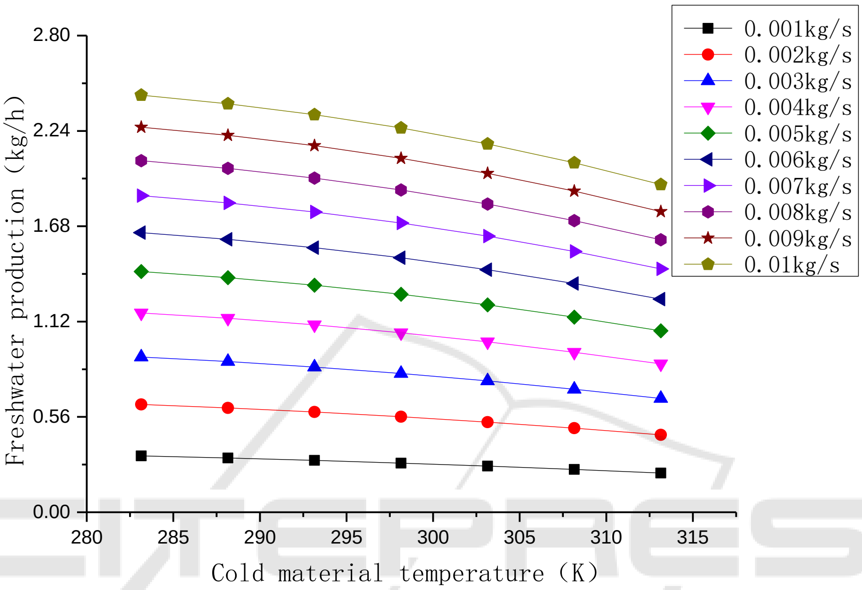

**Figure 5.** Effect of cold feed temperature and flow rate on freshwater production

As can be seen from Figure 5, when the hot material temperature is 85°C, the freshwater yield decreases as the temperature of the cold material increases. Contrary to the effect of increasing hot material temperature, when increase the temperature of the cold material, which reduces the temperature difference between the evaporator and the condenser, reduces the vapour pressure difference, reduces the diffusion drive force, so decreases the diffusion flux.

### 3.2. *Effect of flow rate*

As can be seen from Figure 4 and Figure 5, the production of freshwater increases with the increase of flow rate (from 0.001 kg/s to 0.01 kg/s). This is because the increase of flow rate is much larger than the increase of freshwater production, heat transfer between evaporator and condenser is small compared to the increase in flow rate, the temperature difference between the evaporator and the condenser increases, so the diffusion flux increases.

## 4. Conclusions

Diffusion-Gap Distillation is a new type of thermal seawater desalination process. The device has a large surface area, the operation process does not require a vacuum environment and can realize energy recycling, it can be used widely, such as seawater desalination, treatment of high saltwater, recycle of waste water and so on, has a good application prospect. Using the established model to simulate the process, the results show: increasing the temperature of the hot material can increase the diffusion flux and improve the efficiency; increasing the cold material temperature will reduce the diffusion flux and reduce the freshwater yield; as the flow increases, the output of freshwater increases.

## Acknowledgement

We are deeply indebted to the National Natural Science Foundation of China (Grant No. 51276029) for its funding.

## References

[1] Zheng Z, Li F, Li Q and et al 2016 Desalination Technology Applied Research and Development Status *J. SCIENCE CHINA PRESS* 61(21):2344-2370

[2] Khayet M, Song P and Gang 2011 *Membrane distillation: principles and applications M.* Elsevier

[3] Alklaibi A M and Lior N 2005 Membrane-distillation desalination: Status and potential *J. Desalination* 171(2):111-131

[4] Ge Q, Wang P, Wan C and et al 2012 Polyelectrolyte-promoted forward osmosis-membrane distillation (FO-MD) hybrid process for dye wastewater treatment *J. Environmental Science & Technology* 46(11):6236

[5] Xie M, Nghiem L D, Price W E and et al 2013 A forward osmosis-membrane distillation hybrid process for direct sewer mining: system performance and limitations *J. Environmental Science & Technology* 47(23):13486

[6] Han G, Zuo J, Wan C and et al 2015 Hybrid Pressure Retarded Osmosis−Membrane Distillation (PRO−MD) Process for Osmotic Power and Clean Water Generation *J. Environmental Science Water Research & Technology* 1(4):507-515

[7] Long R, Li B, Liu Z and et al 2017 Hybrid membrane distillation-reverse electrodialysis electricity generation system to harvest low-grade thermal energy *J. Journal of Membrane Science* 525:107-115

[8] Lowenstein A, Slayzak S and Kozubal E 2006 *A Zero Carryover Liquid-Desiccant Air Conditioner for Solar Applications J.*:397-407

[9] Miller J A and Lowenstein A 1991 THE FIELD OPERATION OF A THERMALLY DRIVEN LIQUID-DESICCANT AIR CONDITIONER *J. Aging Clinical & Experimental Research* 3(4):303-304

[10] Lin S, Yip N Y and Elimelech M 2014 Direct contact membrane distillation with heat recovery: Thermodynamic insights from module scale modeling *J. Journal of Membrane Science* 453(3):498-515