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# Distilled Water Production by Vacuum Heat Pump

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Additional information is available at the end of the chapter

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## Abstract

A new machine to produce distilled water was provided, which includes a heat pump system and a vacuum system. And in the vacuum system of this new machine, the ejector is the key component. Three kinds of ejectors were studied by using FLUENT software to simulate their parameters. The simulation results showed that a vacuum is formed in the ejector throat, where the speed also reached its maximum value. The optimized ratio between the area of the throat and that of the mixing section can be obtained according to theoretical calculations. The ejector with the ratio 0.0156 can be used to prepare distilled water, and the experimental results show that the energy consumption of 1 kilogram distilled water is lower than 0.3 kWh. In the heat pump system, the capillary is the key component. Five kinds of capillaries were studied by using CFD software to simulate their parameters. The simulation results showed that the larger the degree of supercooling of the refrigerant in the capillary, the larger the liquid volume fraction of the outlet refrigerant. The experimental results show that suitable capillary can greatly improve the efficiency of the system.

**Keywords:** ejector, simulate, the ratio of ejector, distilled water, capillary tube, condensate depression, energy conservation optimization

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## 1. Introduction

With the development of economy, the problems of water resource shortage and energy shortages appeared in more and more countries and regions. At the same time, people also have increasing demands on the quality and quantity of water, so the research of water treatment and purification has never been stopped.

Although 70% of the earth is covered by water, the freshwater that people depend on is only 2.5–3% of the total water, and the entire world is facing a serious shortage of fresh water resources. In China [1], for example, China's total water resources for  $2.81 \times 10^4$  one hundred

million tons, accounting for sixth place in the world. However, per capita water resources in the global rankings are 108 in China, and China is one of the most water-short countries in 21 poor countries in the world, and water per capita fresh water is only  $\frac{1}{4}$  times the world average per capita. And in 2010, the total water demand was 730 billion tons in China, but the water supply was only 6200~6300 billion tons. By 2030, the water deficit will be higher than 100 billion cubic meters in 2010, and the amount of water per capita will fall to  $1760\text{ m}^3$ . The most severe water shortage is in the coastal industrial cities, where the per capita water resource is much lower than  $500\text{ m}^3$ , which belongs to the severe water shortage area.

Scholars have done a lot of the work on water purification and other aspects, but the principle of the method is not the same, and new methods and new technologies continue to emerge. For example, Sevda et al. [2] use microbial respiration to purify the water, and they have made the single seawater desalination room volume increased from 3 ml to 15 L. There are also a lot of traditional researches on the distilled water by evaporation pipe, for example, Hegazy [3] collected the water through a vacuum evaporator to collect steam condensation, and the energy consumption is about  $1.8\text{ Kw/hr/kg}$ ; Mahkamov [4] studied a new type of small and dynamic solar desalination device, where the piston converter was driven by solar energy and with periodic changes in volume and pressure, in which the purified water can be collected in evaporation tube. There are also many scholars who used membrane technology to produce distilled water. For example, Deshmukh et al. [5] studied the desalination by forward osmosis, and they summed up quantitative results between the structure parameters of the support layer with reduced film area in a certain range, thereby saving cost. In the direct contact membrane distillation process, Duong [6] optimized the thermal efficiency of the brine, so that the water recycling rate ranges from 20 to 60% and the energy consumption can be reduced by more than half. Khalifa [7] and other studies have used air gap membrane distillation to produce distilled water, and the influence of feed temperature and air gap width on the system performance was obtained. In addition, solar energy as a clean energy was also widely used to produce distilled water, for example, Reif et al. [8] used solar energy to desalination. Comparing with the conversion of solar energy into electricity, they pointed out that it was more effective and attractive for the system to be converted into heat energy. Sahoo et al. [9] used solar energy for desalination of sea water and polygeneration, reducing the cost and greenhouse gas emissions. Combination of distilled water and refrigeration system has been researched in depth by scholars. For example, Wang [10] studied a high-efficiency combined desalination and refrigeration system based on the LiBr- $\text{H}_2\text{O}$  absorption cycle, getting more high energy utilization rate and lower operating costs. Nada [11] et al. studied the water production rate of distilled water in the process of desiccant air conditioning. Houa et al. [12] used simulation method to verify the feasibility of marine cooling system with seawater cooling and seawater desalination. Chiranjeevi [13] studied the combination of the two-stage seawater desalination and refrigeration system to improve the energy utilization coefficient. Scholars have studied other methods for producing distilled water, for example, Rommerskirchen [14] produced distilled water by using the single module electrode capacitor. Compared to the traditional capacitive deionized, it can produce distilled water continuously. Zhang [15] studied the influence of salt, anionic polyacrylamide, and crude oil on the membrane fouling in the process of polymer flooding. Comparing with the effect of silica gel

and AQSOA-Z02 on distilled water, Youssef [16] summed up the effect of different cooling water temperatures on the two kinds of materials. Ebrahimi [17] studied the use of low-grade heat source for seawater desalination.

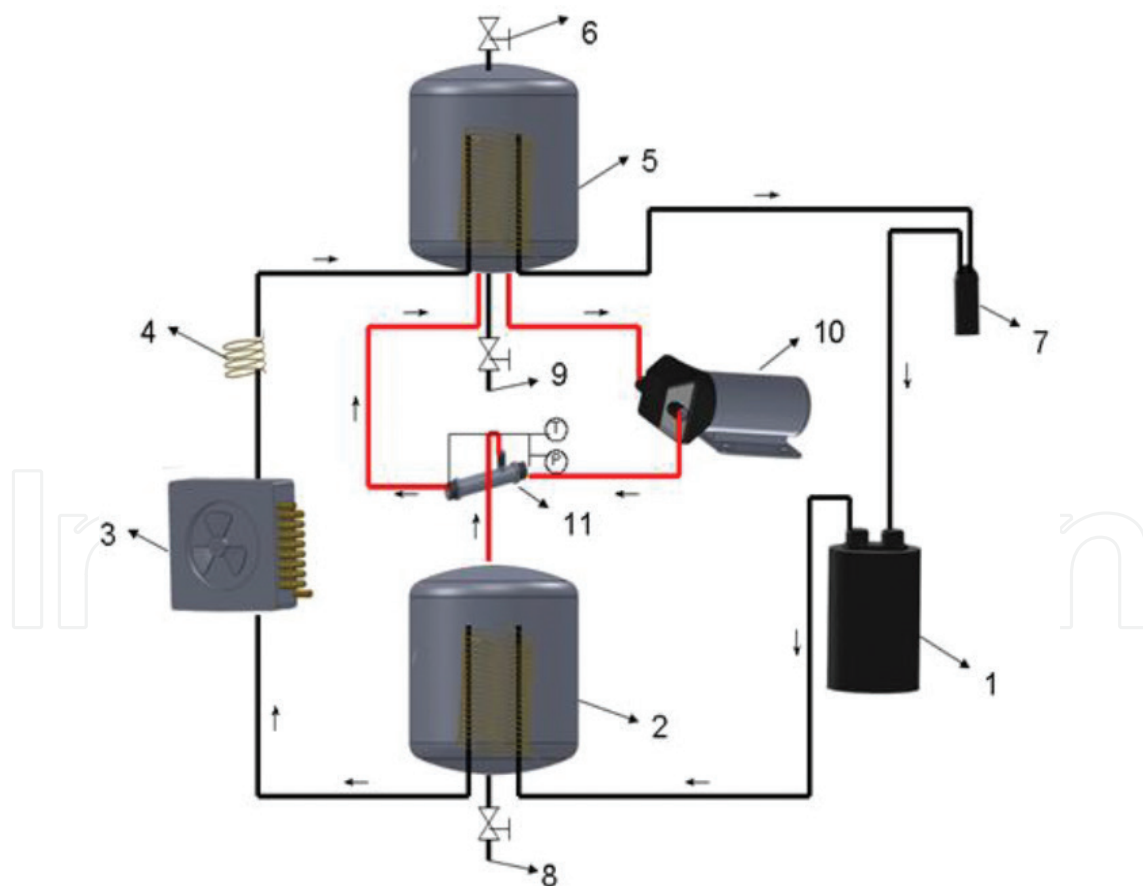
Although the principle of the method for producing distilled water is various, the study on the distilled water by vacuum heat pump is relatively rare. In this paper, the effect of the pressure of the ejector pressure on the production of distilled water is studied.

## 2. System structure

The vacuum heat pump system is shown in **Figure 1**.

The structure of system is divided into two parts: the refrigeration cycle system and the water cycle system.

The principle of refrigeration cycle system is that the high-temperature and high-pressure gas from compressor releases heat when it enters into the vapor generator and auxiliary con-



**Figure 1.** System structure of distilled water. 1, compressor; 2, vapor generator; 3, auxiliary condenser; 4, capillary; 5, condensate absorber; 6, vent valve; 7, gas-liquid separator; 8, water intake; 9, water outlet; 10, high-pressure diaphragm pump; 11, ejector.

denser, and then the gas turns into low-temperature and low-pressure liquid when it flows through the capillary. The liquid will get in the condensate absorber to transfer heat with water vapor. At the end, the low-pressure gas will be back to the compressor after the liquid passing through the gas-liquid separator. In this cycle, the condensing heat of refrigerant is used to produce water vapor by vapor generator, and the evaporative cooling is used to capture water vapor and produce distilled water in condensate absorber.

The work principle of water cycle system is that the water from condensate absorber is sucked by high-pressure diaphragm pump into the ejector, and then the water will be mixed with the vapor sucked by ejector entrainment from vapor generator. After ejector diffuser, the mixture of the vapor and the water returns to the condensate absorber, where the vapor is cooled into distilled water.

2.1. Application of ejector in system

From the working principle of the vacuum heat pump to produce the distilled water, we can find that the function of ejector is of vital importance in this system. The pressure of vapor generator is determined by the sucking pressure resulted from the injecting pressure and velocity of the water. When the injecting pressure is lower, the temperature of the vapor generator is low, so the condensation temperature of the refrigeration system will be reduced and the system efficiency is improved. While the temperature of the condensate absorber is higher, which means a higher temperature of the evaporation temperature of the refrigeration system, it also provides a higher performance of the refrigeration system. **Figure 2** shows the relationship between the water boiling temperature in vapor generator and induced pressure.

It can be seen from **Figure 2**, if a lower water vapor temperature is needed, the lower the induced pressure. When the temperature of water vapor is 30°C, the pressure is 4.25 kPa, and the induced pressure is 7.38kPa at 40°C, which means a very low pressure in vapor generator, so a very good ejector is necessary to obtain an excellent performance of the vacuum heat pump.

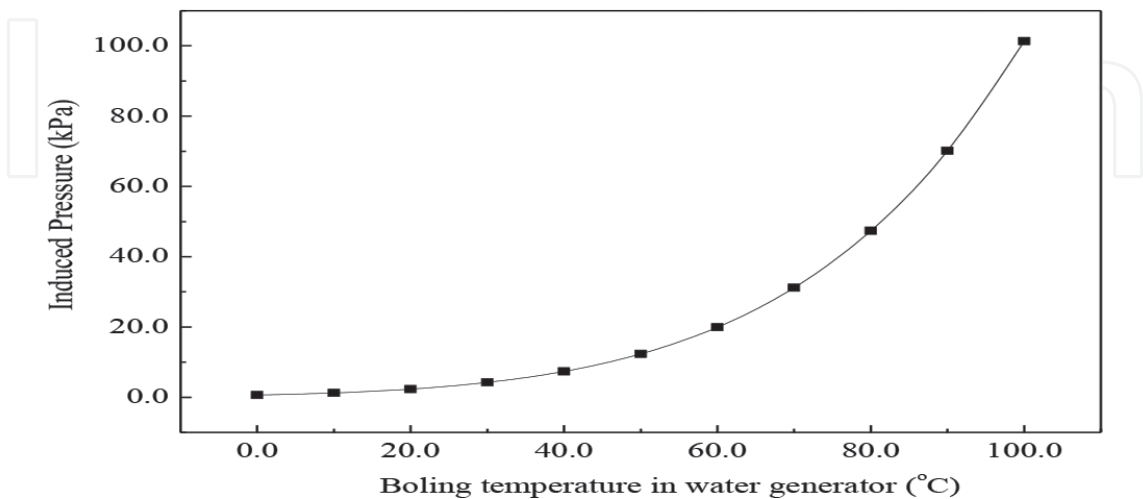


Figure 2. Induced pressure vs. boiling temperature in vapor generator.

2.2. Application of capillary in system

The selection of capillary tubes plays an important role in the system’s energy-saving optimization, it is the component for throttling in the system. The refrigerant is pressurized by a compressor and congealed by a condenser. And it becomes a highpressure liquid and then flows into the capillary tube. Because the inner diameter of the capillary tube is very small, the flow of the refrigerant causes great resistance, and the pressure of the refrigerant is gradually reduced. When the pressure is reduced to the gasification pressure at the temperature of the refrigerant throttling, after the metastable process, the refrigerant is gasification.

In this chapter, CFD simulation and experimental test are performed on the matching of capillary tubes.

3. Design and simulation

3.1. Design and simulation of the ejector

For the ejector, in order to get a low suck pressure for the vapor generator, the spreading ratio (SR) defined as the ratio of the throat area to the tube area should be very small, and the velocity should be very high according to energy conservation. So selecting one optimized ejector to obtain a good performance of the vacuum heat pump system is very important; we designed three ejectors with different spreading ratios, of which the ratios were 0.0156, 0.0532, and 0.0946, respectively, and the throat diameters were 1.5, 3, and 4 mm, respectively, shown in Table 1.

(A)  $SR = 0.0156$  and  $D_t = 1.5\text{ mm}$ ; (B),  $SR = 0.0532$  and  $D_t = 3\text{ mm}$ ; and (C),  $SR = 0.0946$  and  $D_t = 4\text{ mm}$ .

The performance of the above three ejectors were analyzed by FLUENT software. The fluid was the water, the inlet pressure was 0.6 MPa, and the inlet velocity is 1.6 m/s. The simulated results were shown in Figure 3.

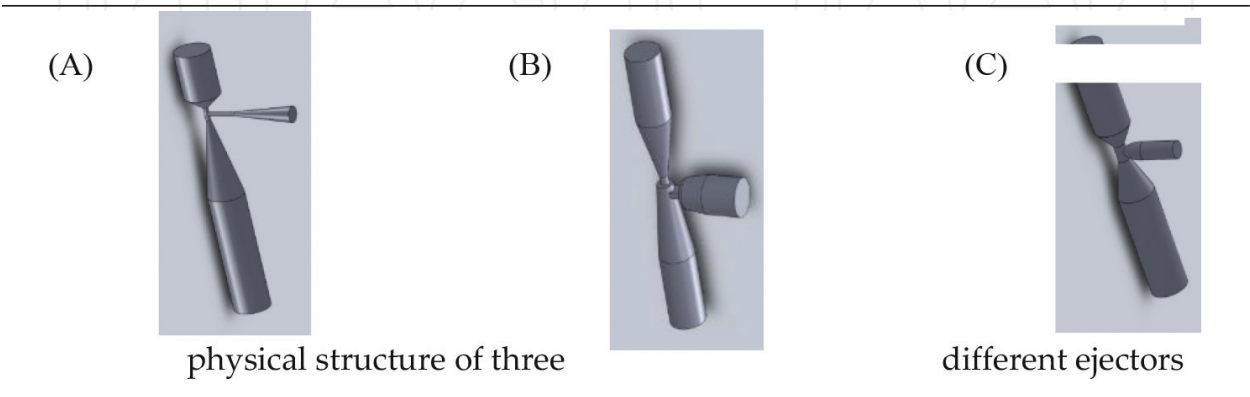


Table 1. Physical structure of three different ejectors 3-a:SR=0.0156,Dt=1.5mm, 3-b:SR=0.0532,Dt=3mm, 3-c:SR=0.0946,Dt=4mm.



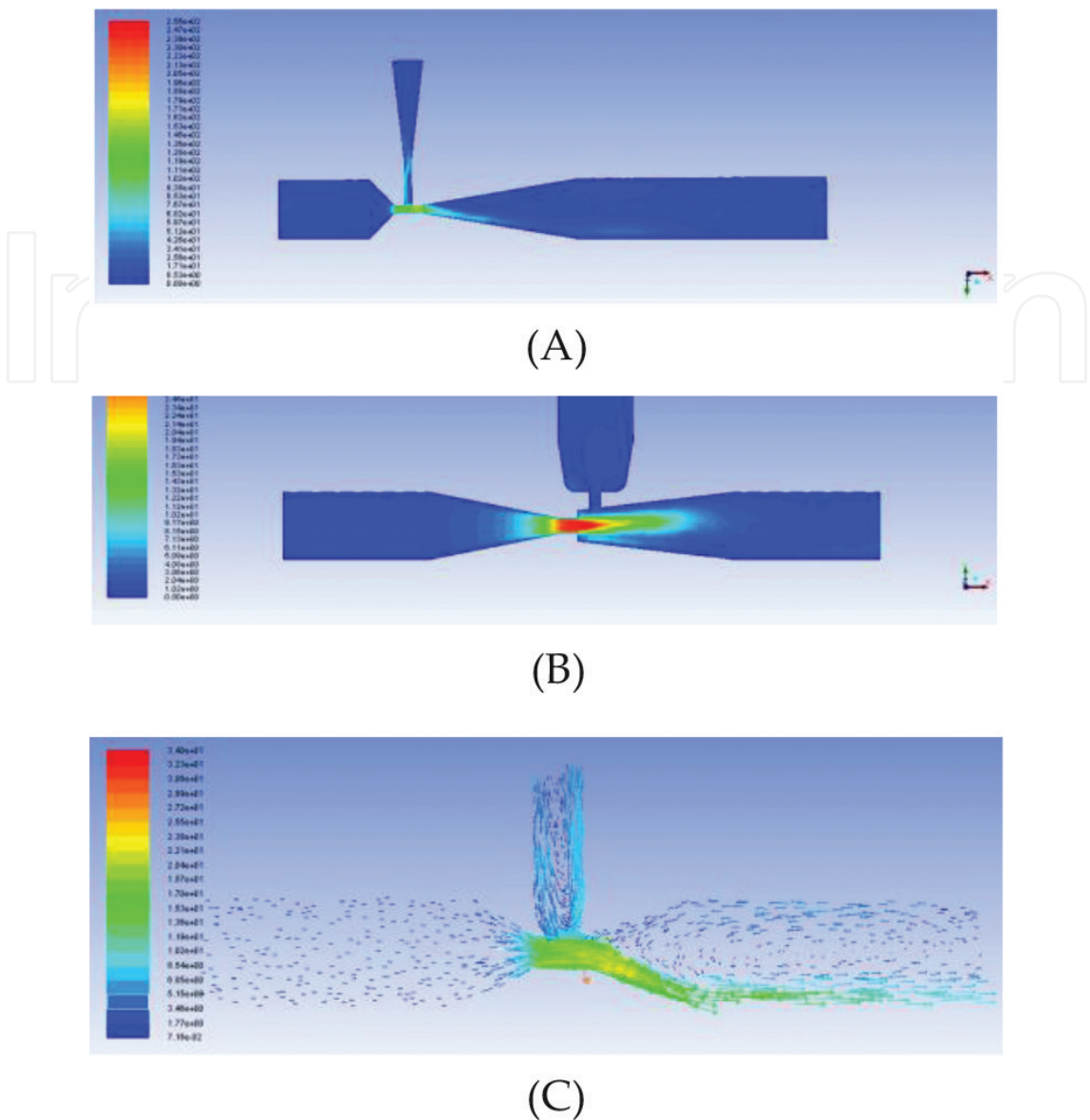
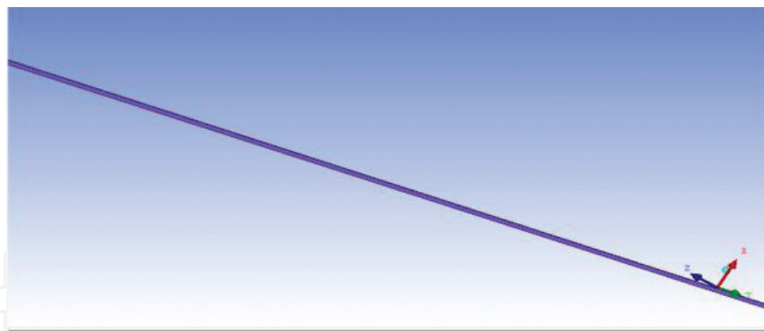


Figure 3. Internal velocity distribution of ejector.

From **Figure 3**, it can be seen that the maximum speed of the ejector (A) throat is 110 m/s and the velocity of the water vapor injection is more than 50 m/s. Compared with the ejector (B), the maximum speed of the throat is 30 m/s, and the velocity of the steam injection is about 4 m/s. While as the ejector (C), there was a reverse flow in the suck line, which implied that the water vapor from the vapor generator cannot be sucked into the condensate absorber. This can be analyzed from the perspective of conservation of energy.

3.2. Design and simulation of the capillary

The capillary tube is a small tube with small inner diameter. Due to the small inner diameter, when the fluid flows through the capillary tube, it will be greatly frictional resistance



**Figure 4.** Capillary grid division.

of the inner wall, and the pressure of the fluid will gradually decrease. And the flow of refrigerant in capillary tube can be divided into four stages: overcooling phase, single-phase metastable phase, gas–liquid two-phase metastable phase, and gas–liquid phase in thermal equilibrium phase. Therefore, we should choose different sizes of capillary tubes to measure the influence of different types of capillary tubes on the inlet overcooling and refrigerant liquid phase exit volume fraction. It is very important to select an optimized capillary tube to obtain a great system performance of heat pump distilled water, so we designed five capillary tubes with different sizes (inner diameter  $\times$  length, unit mm), of which the sizes were  $1.7 \times 1700$ ,  $1.7 \times 1500$ ,  $1.4 \times 1500$ ,  $1.4 \times 1400$ , and  $1.4 \times 1300$ . The inner diameter of the capillary tube used in the system is 0.5–2 mm, and the length is 1–4 m. The inner diameter and length of each capillary tube are different, but their materials are all copper tubes. After selecting the inner diameter and the length, the flow rate of the capillary tube depends on the difference between the cooling degree, the return air pressure, the suction pressure, and so on.

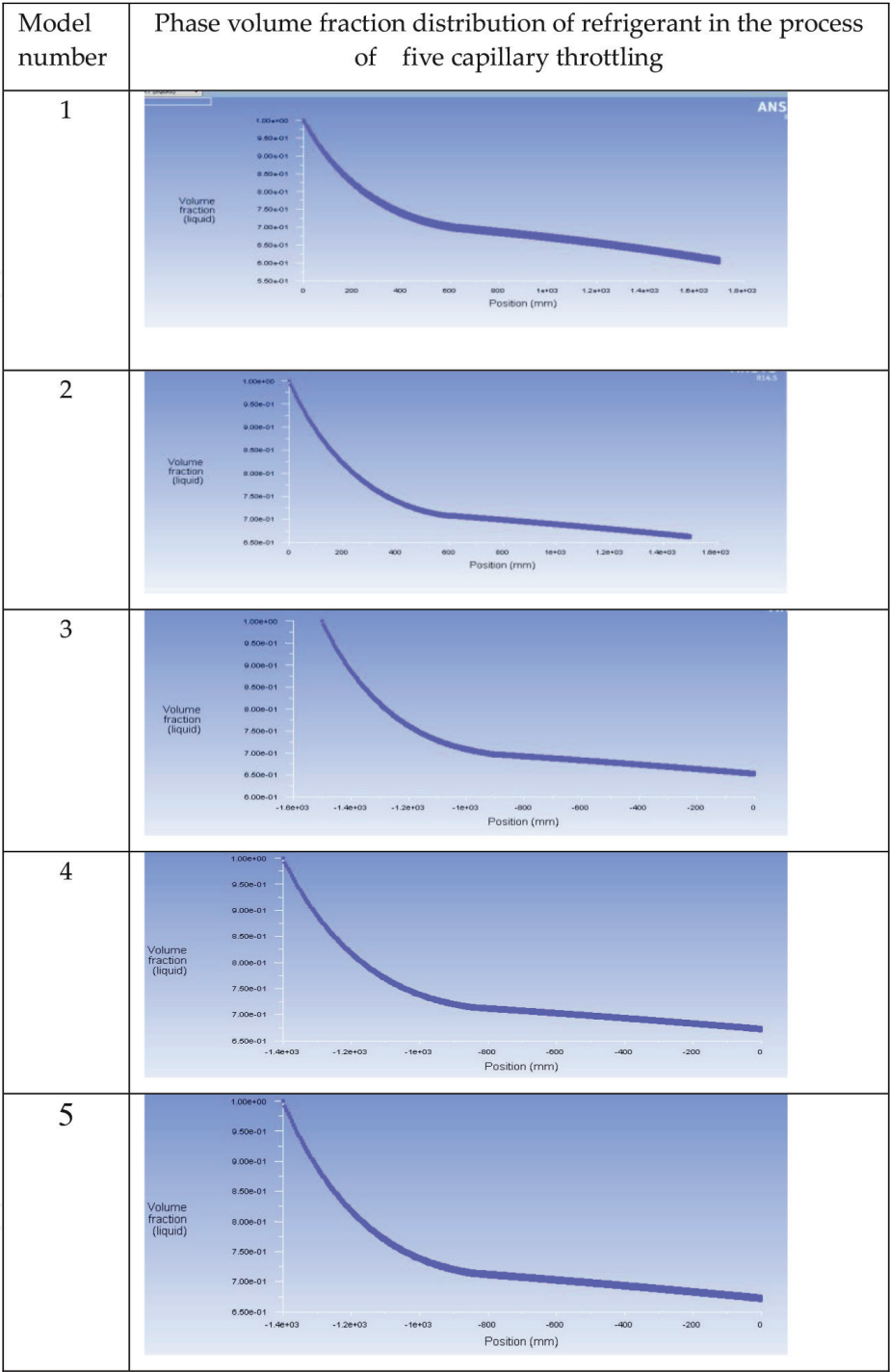
The VOF multiphase flow model is used in the five capillary flow simulations, and the performance is simulated and analyzed by FLUENT software. The fluid is the refrigerant R22, the inlet pressure is 1.8 Mpa, the outlet pressure is 0.6 Mpa, the inlet refrigerant temperature is 314.15 K, and the outlet temperature is 279.16 K.

Capillary tube is a slender structure; the length is greater than the diameter, if only using unstructured grid and drawing the number of grid will be too much; it is easy to exceed the limits of computer processing, so here structured grids are used, internal for hexahedral grid and external for tetrahedron, mesh model as shown in **Figure 4**.

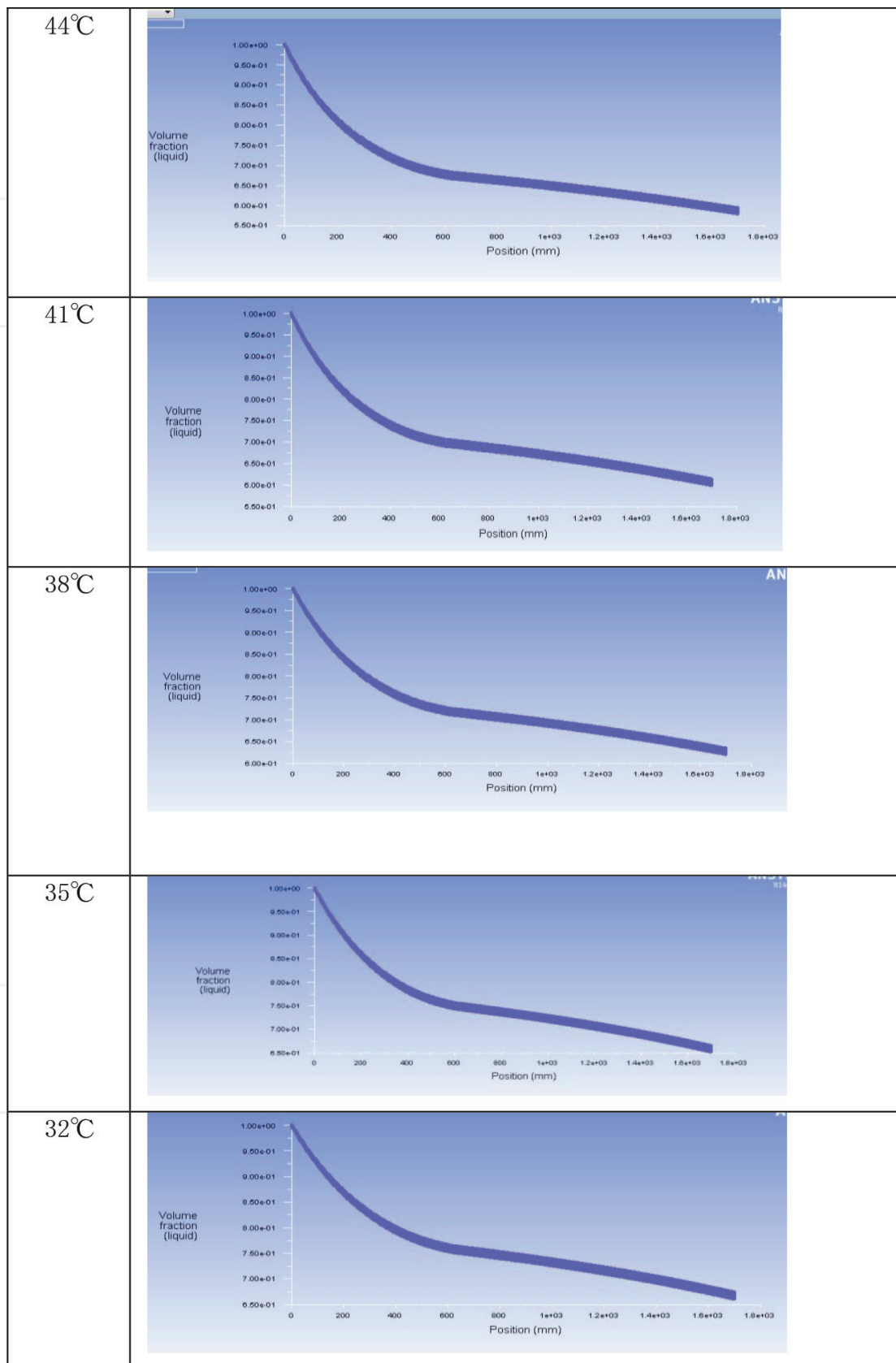
At the inlet pressure which is 1.8 Mpa, the saturation temperature of the refrigerant R22 is 47°C; before entering capillary refrigerant is supercooled. Of five kinds of capillary tube in experimental conditions, the coolant temperature in the entrance of the capillary tube is 41°C, namely, supercooling degree is 6°C; the five models of capillary throttling effect comparing simulation diagram are:

1. Inlet coolant temperature is 41°C, liquid phase distribution of refrigerant in different types of capillary tubes is as follows:





As you can see from the figure above, the shape of the liquid phase change of the five types of capillary tube is similar; the refrigerant gasification rate is faster in the first half of the tube, with the gradual reduction of the refrigerant in the liquid phase; the amount of heat added to refrigerant gasification is also decreasing; this leads to a gradual decrease in the gasification rate of the refrigerant. Obviously, the volume fractions of the liquid phase of the refrigerant after the throttling are, respectively, 5, 4, 2, 3, and 1. The larger the volume fraction of the liquid in the capillary tube, the less the flash gas caused by throttling, the better the system.



**Figure 5.** The liquid phase distribution of the refrigerant in capillary tube No. 1 was different.

1. The volume distribution of refrigerant liquid phase in the same type of capillary tube:

In order to study the effect of the cooling degree on the volume fraction of the liquid phase of the capillary export refrigerant, this simulation simulated the distribution of the liquid phase of the refrigerant under five degrees of supercooling for each type of capillary. In this system, before throttling the refrigerant saturation temperature is 47°C. And every 3°C, select a temperature value for degree of supercooling and the selected temperatures are respectively 44, 41, 38, 35, 32, as shown in **Figures 5**. And we only focus on the experiment diagram of capillary No. 1, and the phase volume fraction distribution of refrigerant in the process of capillary throttling of the other four capillary tubes is uniformly expressed in **Table 2**.

According to the results of comprehensive simulation analysis, the volume fraction of the liquid phase of the liquid phase of the five types of capillary tubes shows the trend

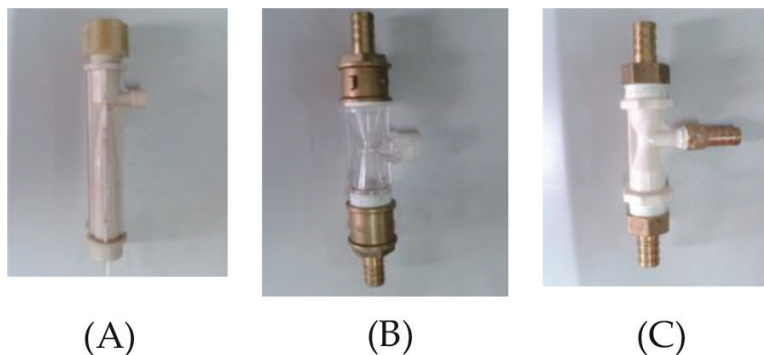
Number of capillaries	Temperature (°C)	Max position (mm)	Max position with its volume fraction (liquid)	Min position (mm)	Min position with its volume fraction (liquid)
2	44	0	1	1500	0.64
	41	0	1	1500	0.646
	38	0	1	1500	0.659
	35	0	1	1500	0.706
	32	0	1	1500	0.732
3	44	-1500	1	0	0.634
	41	-1500	1	0	0.649
	38	-1500	1	0	0.627
	35	-1500	1	0	0.695
	32	-1500	1	0	0.722
4	44	-1400	1	0	0.654
	41	-1400	1	0	0.669
	38	-1400	1	0	0.696
	35	-1400	1	0	0.72
	32	-1400	1	0	0.745
5	44	-1300	1	0	0.68
	41	-1300	1	0	0.695
	38	-1300	1	0	0.723
	35	-1300	1	0	0.739
	32	-1300	1	0	0.769

**Table 2.** The maximum and minimum position with their volume fractions of other capillaries at different temperatures.

of increasing with the increase of the supercooling degree. Therefore, under certain conditions, the higher the degree of supercooling, the less flash gas produced by throttling, the higher the volume fraction of the liquid component of refrigerant. Combined with the experiment, the entry refrigerants  $41^{\circ}\text{C}$  under 1, 2, 3, 4, and 5 capillary outlet refrigerant liquid volume fractions are, respectively, 0.599, 0.646, 0.649, 0.646, and 0.649; it has already satisfied the requirements of heat pump system. Comprehensive to the practical situation and design experience of heat pump system, this system selects the supercooling degree at  $6^{\circ}\text{C}$ , and the temperature of the refrigerant before the throttling is  $41^{\circ}\text{C}$  as the temperature of the capillary inlet refrigerant.

## 4. Results and discussion of the experiment

### 4.1. Experimental results and discussion of ejector



A set of experimental transposition was designed to verify the possibility of producing distilled water by the ejector. The main equipment include compressor (2R11B225A), pump (DP-35), condensation absorber (diameter 100 mm and height 300 mm), water generator (diameter 100 mm and height 300 mm), and capillary (length of 400 mm and diameter 2 mm). The above three kinds of forms of ejector were tested. Ejector C failed to form steam ejector function, so **Figure 6** shows throat pressure of the ejectors (A) and (B) versus time.

From **Figure 6**, it can be seen that the minimum pressure of ejector A can reach  $-0.085\text{ Pa}$ , the corresponding water vapor generator temperature at  $50^{\circ}\text{C}$ , and it can produce very good water vapor ejector effect, meeting the temperature requirements of the condenser of the refrigeration system. The lowest pressure can reach  $-0.034\text{ Pa}$ , the corresponding water vapor generator temperature at  $73^{\circ}\text{C}$ , but at this temperature, the efficiency of the refrigeration system will be very low. **Figure 8** is the fluid state of the ejector in the experiments.

From **Figure 7**, it can be seen that there is a mixed fluid of water and vapor in the ejectors A and B, while the ejector C produces the backflow, which cannot form an effective water vapor ejector effect. The ejector A is selected as a system unit, and the three different powers of the compressor were used in the production of distilled water. **Table 3** is the amount of distilled water produced by three experiments.

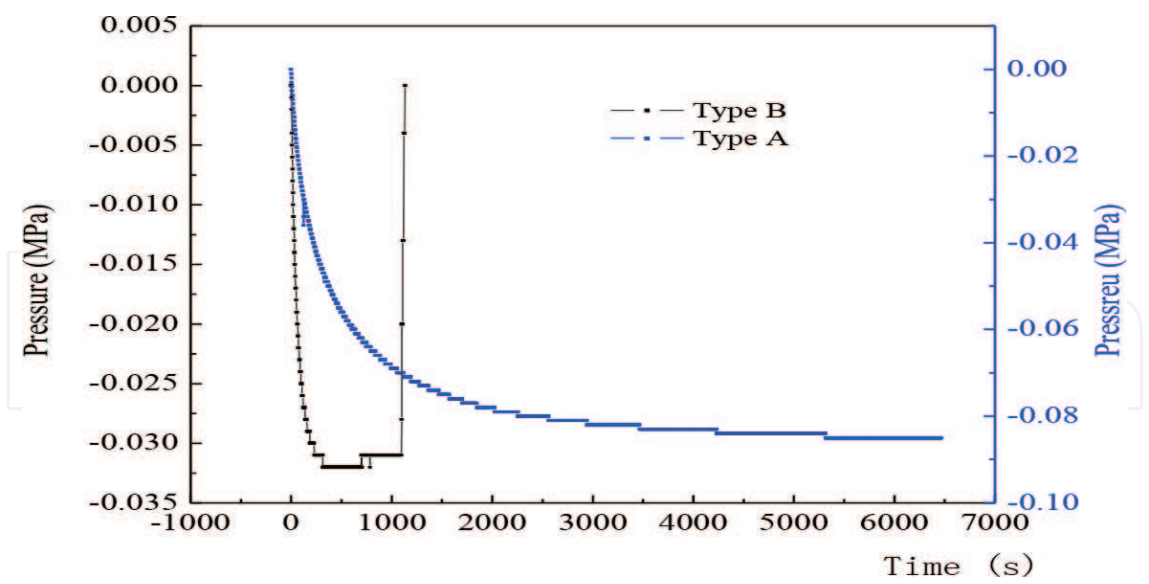


Figure 6. Throat pressure of ejector (a) and ejector (B) vs. time.

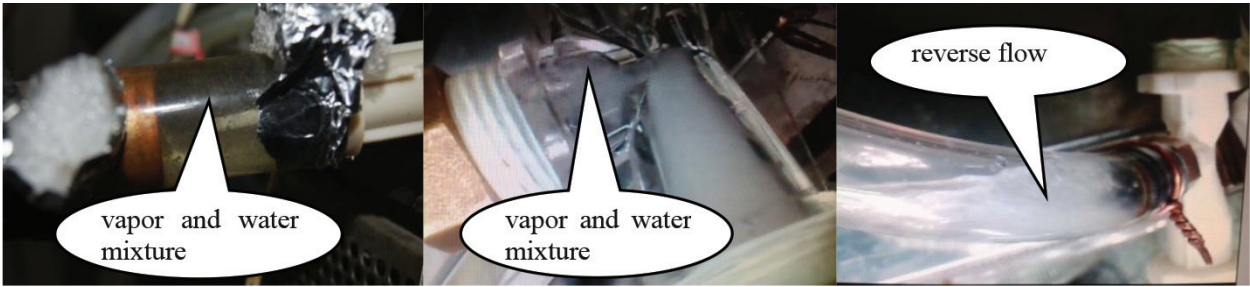


Figure 7. The flow state of the water vapor in the ejector.

From **Table 3**, it can be seen that the whole distillation water device runs stably under ejector A, and the water output per unit of electricity is more than 4.7 kg, the energy efficiency of which can be calculated by the following equation:

$$\varphi = \frac{Q}{P} \quad (1)$$

where Q is the heat produced by distilled water (kJ) and P is the power consumed (kJ). Therefore, the energy efficiency of this device is  $\varphi = \frac{4.7 \times 2400}{3600} = 3.13$



Figure 8. Five different types of the capillary.

Experiment number	Compressor type	Effluent (kg)	Energy consumption (kWhr)	Unit energy consumption (kg/(kWhr))
1	TH31	9.8	2	4.90
2	PG108X1	4.8	0.98	4.90
3	KH145	5.2	1.1	4.73

**Table 3.** Quantity of distilled water produced.

#### 4.2. Experimental results and discussion of capillary

A set of experimental equipment was designed to study the problem of capillary matching for a heat pump distiller. The main equipment include compressor (Panasonic centrifugal compressor, 220 V, 50 Hz, 1700 w), swap body (diameter 15 mm and height 27 cm), frozen water tank (length 30 cm, width 30 cm, and height 40 cm), ejector (inlet diameter 6.5 cm, nozzle diameter 1.2 mm, and speed of evacuation 15 L/s), valve (DC2 4 V), and five different types of capillary tubes, as shown in **Figure 8**.

The simulation test of these five capillary tubes found that the capillary tubes No. 1 and No. 2 were most suitable for this system, where No. 2 was slightly worse than No. 1, and the other three kinds of capillaries were not suitable for the system. And then we are just going to think about the simulation results for the No. 1 and No. 2. **Table 4** shows the voltage, current, and temperature of capillary tube No. 1 and No. 2. **Table 5** shows the electric energy per hour of the system under the capillary No. 1 and No. 2. **Table 6** shows the yield and energy efficiency of the distilled water under No. 1 and No. 2.

Number of capillaries	Sizes (inner diameter × length, unit mm)	Voltage (V)	Electricity (A)	Compressor power (W)	Compressor average power (W)
1	1.7 × 1700	220	2.7	594	608.7
		220	2.8	616	
		220	2.8	616	
2	1.7 × 1500	220	2.8	616	616
		220	2.8	616	
		220	2.8	616	

**Table 4.** The voltage, current, and temperature distribution of the compressor for two most suitable capillaries.

Number of capillaries	Sizes (inner diameter × length, unit mm)	Compressor average power (W)	System power (W)	Consumption of electricity per hour (degree)
1	1.7 × 1700	608.7	716.7	0.7167
2	1.7 × 1500	616	724	0.724

**Table 5.** Electric energy consumption per hour for two most suitable capillaries.



Number of capillaries	sizes (inner diameter × length, unit mm)	Distilled water production (L/h)	Average production (L/h)	Energy efficiency (L/degree)
1	1.7 × 1700	2.1	2.05	2.86
		2.08		
		1.97		
2	1.7 × 1500	1.69	1.76	2.43
		1.88		
		1.72		

**Table 6.** Production and energy efficiency of distilled water of two most suitable capillaries.

Heat pump water distiller is a device that uses electric energy to produce distilled water, and in this article the energy efficiency is defined as the ratio of water production to electricity consumption. And the higher the energy efficiency is, the more distilled water is produced per kWh, and the more energy-efficient the system. The energy consumed by the system is compressor, pump, fan, and circuit board. As the power of the fan is negligible, the total power is combined with the power of the compressor and the pump. Energy efficiency is the key factor to consider the performance of the system. The purpose of energy-saving optimization is to improve the energy efficiency of the system under the condition of ensuring stable operation. Considering the selection of capillary tubes, in terms of energy consumption or energy efficiency, capillary tube No. 1 is superior to capillary tube No. 2. It is the most suitable system for smooth operation and energy saving.

### 5. Conclusion

Utilizing the production of distilled water by heat pump system is a very effective and comprehensive application of energy transposition. The condenser heat is used to generate steam, and then water vapor is caught by the evaporator to produce distilled water. Through the simulation and experimental study of the ejector and capillary, the following conclusions can be drawn:

1. Through theoretical and experimental research, the use of heat pump system to produce distilled water is feasible.
2. The negative pressure produced by the ejector is increasing with the decreasing of the spreading ratio. In this study, the pressure of the ejector can reach the following pressure of -0.85 MPa at the spreading ratio of 0.0156.
3. In this experiment, the amount of distilled water per kilowatt is above 4.7 kg, and the energy efficiency is 3.13.
4. Through theoretical and experimental studies, capillary tube selection plays an important role energy-saving optimization of the system. Suitable capillary can greatly improve the efficiency of the system.
5. Through CFD simulation, it is verified that the greater the degree of supercooling of the refrigerant in the capillary, the larger the liquid volume fraction of the refrigerant at the outlet of the capillary is.

## Author details

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