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Research On Condensation and Evaporation in Gas Wave Refrigerator

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Abstract—Gas wave refrigerator uses movement of pressure waves to realize refrigeration. When high pressure inlet gas contains condensable component, condensation happens in gas wave refrigerator. By means of numerical simulation and experiment, this paper investigates effects of condensation on performance of gas wave refrigerator. The results show that evaporation also exists in gas wave refrigerator. Latent heat released by condensation makes temperature of low temperature region rise. When the gas in high pressure inlet contains saturated water vapor, with the increase of pressure of high pressure inlet, the percentage of reduction of temperature drop firstly rises then drops. Results of experiment show that with the increase of high pressure inlet relative humidity, the temperature drop between high pressure inlet and low temperature outlet decreases. With higher pressure of high pressure inlet, change trend of temperature drop becomes gentle.

Keywords—condensation, evaporation, refrigeration, pressure waves, pressure oscillation tube

I. INTRODUCTION

Gas wave technology takes usage of pressure energy of gas to realize energy transfer, which has an advantage of high isentropic efficiency. Compared with turbine which could also realize high isentropic efficiency energy transfer, gas wave technology depends on movement of pressure waves to work, so it doesn't have to be at high rotational speed [1]. Therefore, the device of the technology is not prone to be damaged and the maintenance cost is relatively low [2]. Besides, theoretically, gas wave technology has higher efficiency of compression than turbine [3].

Since 20th century, NASA in America has been performing experiments about gas wave technology in the field of gas turbine engines and come to some conclusions about design of the device [4-9]. These years, application of gas wave technology to device of small scales has been ongoing in Tokyo University and characteristics of internal flow and heat transfer have been summarized [10]. Gas wave technology has a broad range of international application prospects.

In 1972, gas wave technology was applied in field of refrigeration. Two companies called ELF and BERTEN used a straight tube with one end open and the other closed to build the first heat-separation machine which is now called single-opening gas wave refrigerator [11]. After that, this kind of machine has been developed in many countries [12-13]. However, as for single-opening gas wave refrigerator, if the gas from inlet contains condensable component such as heavy hydrocarbon and water vapor, there will be liquid accumulate at the close end of the tube after gas being cooled, which will corrode the tube [14]. Therefore, a proposal of new structure of gas wave refrigerator is necessary to fix this problem.

In the 20th century, HU et al. proposed to use wave rotor shown in Fig. 1, which is a device composed of tubes with two ends open called pressure oscillation tubes, to realize gas wave refrigeration and developed external circulation dissipative gas wave refrigerator. In pressure oscillation tubes of gas wave refrigerator, the liquid generated by cooled condensable gas could be carried by gas that flows out of the tube through either side of the tube. So the mass of accumulated liquid in pressure oscillation tube would decline and the corrosion problem could be solved to a certain extent. And in external circulation dissipative gas wave refrigerator, the heat energy released by expanded gas in pressure oscillation tube could be recovered so high efficiency refrigeration could be realized [15-18]. After years, on the bases of external circulation dissipative gas wave refrigerator, ZHAO proposed over-expansion gas wave refrigerator, which could convert expansion work of gas to shaft work and realize higher efficiency refrigeration [19].

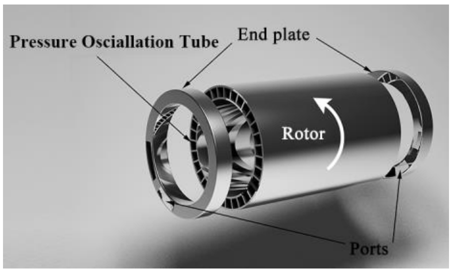


Fig. 1. Gas wave refrigerator

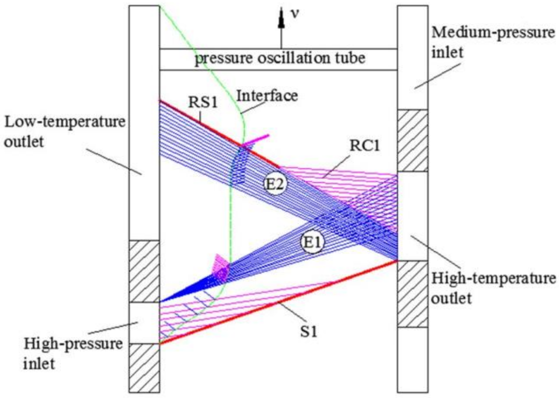


Fig. 2. Wave system in gas wave refrigerator

This paper focuses on external circulation dissipative gas wave refrigerator and its work principle could be explained by 2D ideal wave diagram shown in Fig. 2. When gas wave refrigerator is working, the pressure oscillation tubes move upward periodically. When the tube is connected with high pressure (HP for short) inlet, HP gas injects into the tube and shock wave S1 appears and moves to the right compressing the original gas in the tube. Relatively, at the same time, expansion waves also appear and expand HP gas. Then pressure oscillation tube is connected with high temperature (HT for short) outlet, compressed original gas in the tube discharges from HT outlet. The shock wave S1 reflects a series of expansion waves E1 at the right side of the tube, which makes the pressure and temperature of gas in pressure oscillation tube lower. The gas that flows out of HT outlet flows back to pressure oscillation tube through medium pressure (MP for short) inlet after exchanging heat. At the time pressure oscillation tube leaves HP inlet, another series of expansion waves E2 appears and expand the gas in the tube another time making the temperature and pressure of gas lower again. Finally both sides of pressure oscillation tube start to connect with low temperature (LT for short) outlet and MP inlet and LT gas in pressure oscillation tube flows out through LT outlet pushed by differential pressure between LT outlet and MP inlet. So a cycle of work in gas wave refrigerator is completed.

In industry, as long as refrigeration is involved, there must be condensation. During the process of refrigeration of natural gas, throttle expansion is prone to make the heavy hydrocarbon within natural gas, such as nonane, in super-cooled state and condense to droplets, which would plug pipes [20]. In aerospace industry, water vapor in the air would also condense to droplets in cryogenic wind tunnel [21]. Even in laval nozzle, if the gas that flows in the nozzle contains water vapor, the vapor would be expanded and condense to droplets when the flow becomes supersonic [22]. Equally, as for the flow in gas wave refrigerator, condensation also exists when inlet gas contains condensable component. However, the difference is that, the flow field in gas wave refrigerator is unsteady and the condensable gas is in non-equilibrium state for the most of time, which makes condensation process difficult to describe. Therefore, it is necessary to investigate the condensation behavior in gas wave refrigerator.

II. Preliminary Study

A. Experiment set up

Preliminary study of condensation in gas wave refrigerator could be done by using discrete phase model in numerical simulation. As for the geometric model of gas wave refrigerator, considering the calculating ability of computer and time cost, 2D geometric model of gas wave refrigerator shown in Fig. 3, built by spreading 3D model along the axis, is chosen instead of 3D model. In addition, the ratio of length to diameter of pressure oscillation tube is generally greater than 10, which is enough to regard the flow in the tube as plane flow. The length and width of pressure oscillation tube are separately set 400mm and 13mm. Upward velocity of the tube is set 33m/s to make sure the match of pressure waves. The pressure and temperature of HP inlet, which is defined pressure inlet, are separately set 0.4Mpa and 298K. The pressure of HT outlet and LT outlet, which both are defined pressure outlet, is set 0.1Mpa. Then MP inlet is defined mass flow inlet of which the mass flow rate is equal to that of HT outlet to assure conservation of mass and the temperature of is set 298K. The fluid of the simulation is set ideal air. After grid-independence test, grids of size set as 1.5×1.5 mm×mm are chosen to be used in numerical simulation of gas wave refrigerator. Then periodicity is attached to the model to make sure pressure oscillation tubes could move periodically.

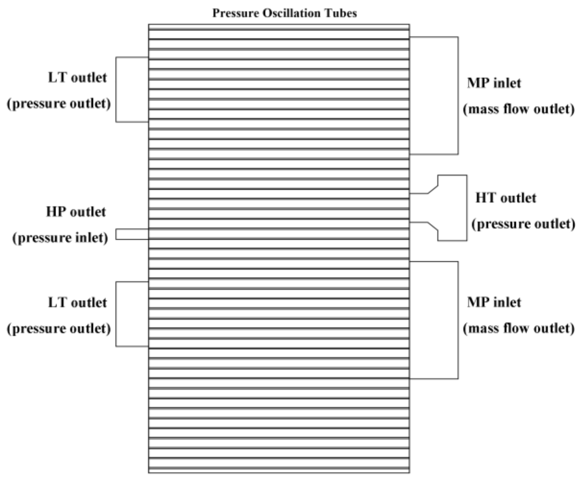


Fig. 3. 2D geometric model of gas wave refrigerator

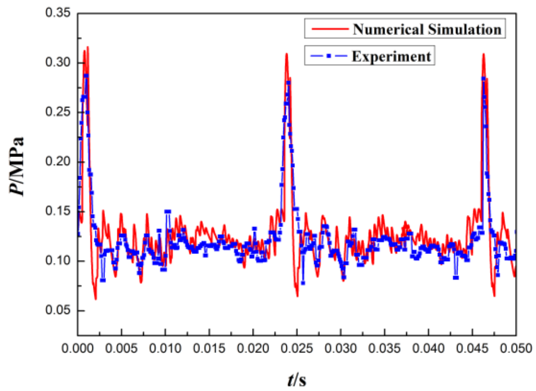


Fig. 4. Comparison of pressure fluctuation between experiment and numerical simulation

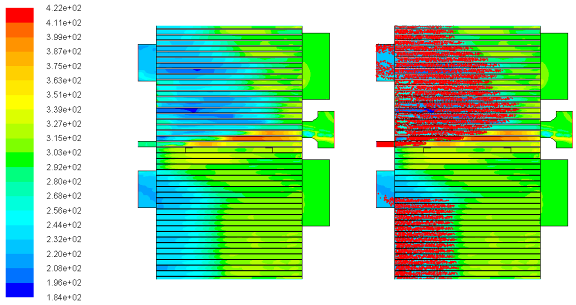


Fig. 5 Temperature and density of particles with diameter 0.1 μm

2D model is confirmed valid by comparing pressure fluctuation from experiment, in which the pressure sensor is set in the pressure oscillation tube, and simulation at the same condition, as shown in Fig. 4.

About discrete phase setup, when gas from HP inlet contains condensable component, condensation generally firstly happens within HP gas when it injects into pressure oscillation tubes, so water droplets injection, interacting with continuous phase, is defined at HP inlet. The mass flow of droplets is equal to that of saturated water vapor at the same condition. In previous study of droplets in unsteady flow, the diameter of most condensed water droplets is not larger than 10μm. Therefore, in different cases, the diameter of droplets flows from HP inlet is separately set 10μm, 1μm and 0.1μm.

From results of numerical simulation, which is shown from Fig. 5 to Fig. 7, combining the temperature contour and particle density, it can be seen that, most of droplets stay in the region where temperature is relatively low in the pressure oscillation tube. For droplets of which the diameter is 0.1μm and 1μm, there are few particles flow from the left LT region into the right region where the temperature is higher than LT region. However, near the interface between two regions where heat conduction is dramatic, there are quite a few particles. These droplets arrive at the interface after being carried by LT gas and condensing in LT region, so they are going to be heated and evaporate near the interface because of heat of HT region.

For particles of which the diameter is 10μm, because of inertia, droplets not only stay near the interface of dramatic conduction, they even get through the interface and stay in the region where temperature is higher than the left LT region. In addition, a small quantity of droplets gets exhausted through HT outlet. So that further proves that there is the possibility that droplets would reach HT region after passing through the LT region.

Besides, particles of 1μm and 10μm are not fully exhausted out of LT outlet. There are droplets remain in pressure oscillation tubes after one cycle. In next work cycle, these droplets would get compressed by shock wave S1 and evaporate. Therefore, when HP inlet gas contains condensable component, there is not only condensation in gas wave refrigerator but also evaporation.

III. MOVEMENT ANALYSIS OF PARTICLES

For further study of condensation and evaporation in gas wave refrigerator, experiment and numerical simulation combined with condensation and evaporation is carried out.

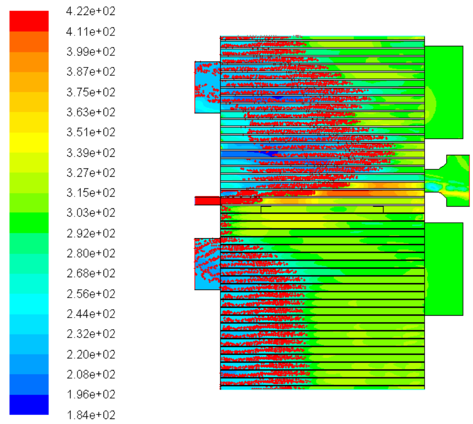


Fig. 6 Density of particles with diameter 1 μm

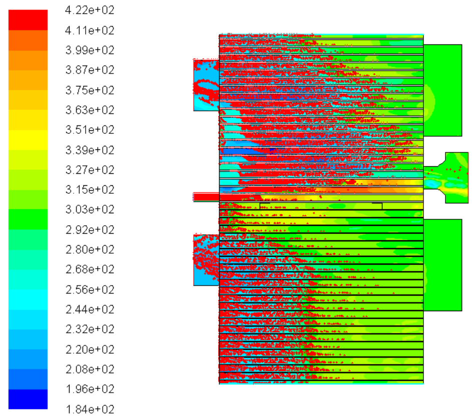


Fig. 7 Density of particles with diameter 10μm

A. *Experiment set up and numerical model*

Experiment platform of gas wave refrigeration is built up, which is shown in Fig. 8. The experimental process is shown in Fig. 9. The gas from HP gas source flows into two pipelines. In one pipeline HP air obtains saturated water vapor after flowing through atomizer and swirl filter. In the other pipeline, air gets totally dried by adsorption dryer and become dry air source. By controlling and mixing the mass flow rate of either pipeline, the relative humidity of HP inlet gas could be adjusted from 0 to 1. Moisture analyzer is set on HP inlet and the relative humidity of gas could be monitored. A heat exchanger is installed to make sure the gas flows out of HT outlet could exchange heat with cool water before flowing back to MP inlet.

The assumptions used in this study are as follows: velocity slip between droplets and gas is neglected, volume and interaction of droplets are neglected, internal temperature of droplets is homogeneous and there is no foreign particles in the flow such as ionic and dust. So the nucleation could be regarded as homogeneous nucleation. The nucleation rate J is as follows [23]:

$$J = \frac{q_c}{1+\phi}\left(\frac{\rho_v^2}{\rho_l}\right)\left(\frac{2\sigma}{\pi M_m^3}\right)^{1/2}\exp\left(-\frac{4\pi r_*^2\sigma}{3kT}\right) \quad (1)$$

$$\phi = \frac{2(\gamma-1)}{\gamma+1}\left[\frac{h_{lg}}{RT_g}-\frac{1}{2}\right]^2 \quad (2)$$

Fig. 8. Gas wave refrigerator experimental platform

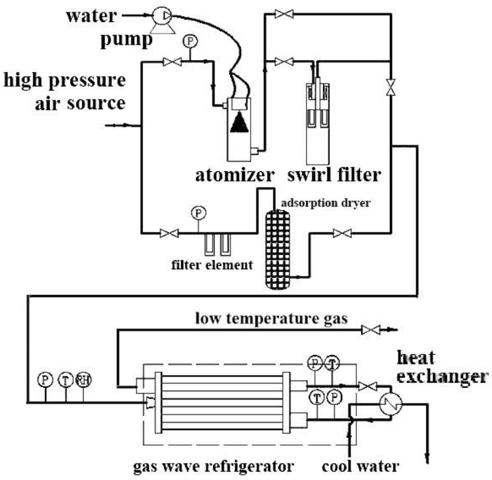


Fig. 9. Schematic diagram of experimental process

Where (2) is non-isothermal correction factor, σ is surface tension, q_c is the coefficient of condensation, M_m is the molecular mass of the condensable component, k is Boltzmann constant.

The Hertz-Knudsen equation is adopted for the droplet growth and evaporation model [24-25]:

$$\frac{dr}{dt} = \frac{p_v - p_{sr}}{\rho\sqrt{2\pi RT}} \quad (3)$$

p_{sr} is the surface saturation vapor pressure of droplet, which is:

$$p_{sr} = p_s \exp\left(\frac{2\sigma}{\rho RT}\right) \quad (4)$$

In order to verify the condensation-evaporation model used in numerical simulation, the pulse expansion wave tube, where the flow field is similar to that in the pressure oscillation tube, is used for comparison.

Pulse expansion wave tube is shown in Fig. 10. The rupture of film between high pressure section (HPS for short) and low pressure section (LPS for short) will produce a series of expansion waves, leading to condensation and decrease of the pressure at measuring point P. At the same time, a shock wave running to LPS is also generated. The shock wave reflects at the sudden enlargement position to generate the expansion wave to promote the growth of droplets further. The shock wave then reflects at the wall at the end of LPS and a series of reverse compression wave is generated, which could cause the evaporation of droplets at P point and the decrease of radius.

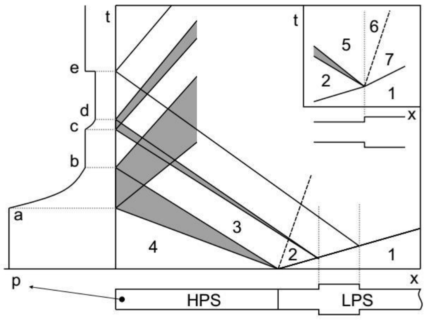


Fig. 10 Wave system in pulse expansion wave tube

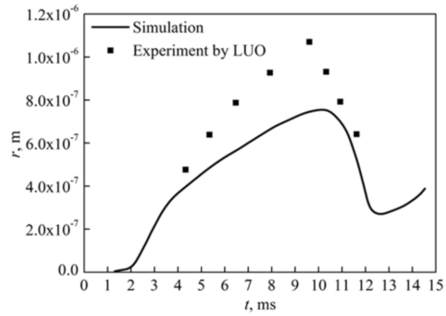


Fig. 11 Validation for evaporation and condensation model

The radius of droplets at the point P is monitored in numerical simulation and experiments which is done by LUO [26]. The curve of radius is shown in Fig. 11, which shows that the change trend of droplet radius in the numerical simulation is consistent with the experiment, and the value of droplet radius is similar to measured value, indicating that the condensation-evaporation model established in this paper is feasible.

B. *Investigation results*

To clarify the influence of condensation and evaporation on refrigeration performance of pressure oscillation tube, as for numerical simulation, in each operation condition, two cases are simulated. One is combined with condensation-evaporation model, the other is not. So that difference between two cases could be found out and the influence of condensation and evaporation could be figured out.

For boundary conditions, the pressure of LT outlet and HT outlet is set 0.1Mpa. The temperature of MP inlet is 298K and the mass flow rate is kept the same as HT outlet. The move speed of pressure oscillation tubes is still 33m/s upward. About HP inlet, the pressure is set three values in different conditions from 0.2Mpa to 0.4Mpa and the temperature is 298K. The species of the gas of HP inlet is defined the mixture of air and saturated water vapor.

In results of numerical simulation, pressure contour with pressure of HP inlet is 0.4Mpa is shown in Fig. 12. Compared with the case without condensation-evaporation model, the temperature contour with condensation-evaporation model seems different. A series of relatively weak compression waves, which are the result of condensation of droplets, could be seen in the low temperature region of temperature contour in the case with condensation-evaporation model. This is because that condensation of droplets would release latent heat of water vapor and reduce the mass of water vapor, which would generate pressure waves and affect temperature and internal flow within pressure oscillation tubes. The pressure waves that produced by evaporation of droplets could not be seen accurately because the number of droplets that evaporate is much smaller than the all droplets in pressure oscillation tube.

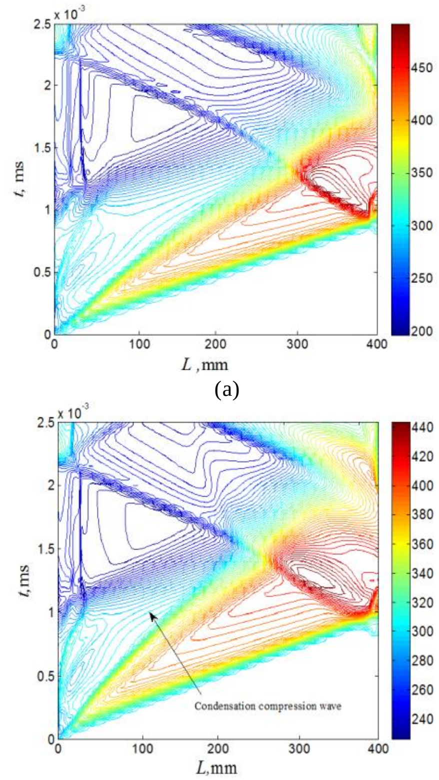
The temperature contour of the results of numerical simulation, as shown in Fig. 13, could present the effect of condensation and evaporation on refrigeration performance more apparently. Because of the heat released by condensation, temperature of some LT parts in pressure oscillation tube, which are marked in Fig. 13, is higher, compared with the contour without condensation-evaporation model.

The effect extent of additional pressure waves generated by condensation-evaporation could be quantified by percentage of reduction of temperature drop between HP inlet and LT outlet, compared with the case without condensation-evaporation model. In Fig. 14, the percentage is presented at different pressure of HP inlet. It is clear that condensation and evaporation make the temperature drop between HP inlet and LT outlet of gas wave refrigerator decline. Besides, with the increase of pressure of HP inlet, the percentage of reduction of temperature drop firstly rises then drops.

This could be explained that, higher pressure of HP inlet would generate more powerful expansion wave when the pressure oscillation tube is connected with HP inlet. Then the gas mixture of air and water vapor would be expanded more, which is more conductive to condensation of water vapor. Therefore, condensation is more and the latent heat that released by condensation is more, which makes the temperature of LT outlet higher. When the pressure of HP inlet is high enough, which is able to make all of the water vapor condense, the latent heat released reaches its maximum, but the power of expansion wave still rises with the increase of pressure of HP inlet, which means the cold caused by HP inlet still increases. So the percentage of reduction of temperature drop decreases after peak value.

The relation of humidity of HP inlet gas to refrigeration performance of gas wave refrigerator could be figured out in experiments by adjusting the pressure and the relative humidity of HP inlet. Relative humidity of HP inlet is adjusted from 0 to 1 and the temperature is set constantly 288K during the process of experiment. The pressure of HP inlet is set 0.2Mpa and 0.3Mpa. The pressure of other inlet or outlet is kept 0.1Mpa. The temperature of the backflow to MP inlet is kept 298K by heat exchanger and LT outlet is connected to atmosphere of which the temperature is 298K.

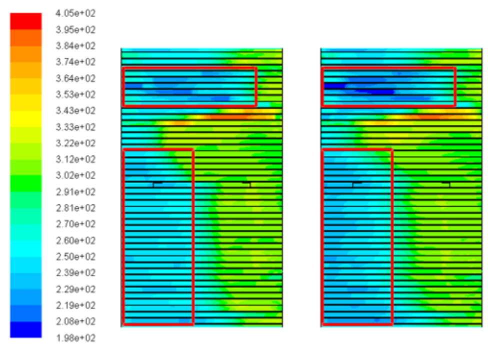
The result is shown in Fig. 15, from which it can be seen that with the increase of relative humidity of HP inlet, the temperature drop between HP inlet and LT outlet decreases. When pressure of HP inlet is 0.3Mpa, the difference of temperature drop between 0 and 1 of relative humidity is 3K. For that of 0.2Mpa, it is 4K. Which is, compared with the case when pressure of HP inlet is 0.2Mpa, the decline of temperature drop becomes gentler with 0.3MPa. This is because that latent heat released by condensation becomes more when relative humidity of HP inlet rises. The heat makes the temperature of LT outlet gas rise, so the temperature drop decreases, which degenerate the refrigeration performance of gas wave refrigerator. With the same relative humidity of HP inlet, the pressure of HP inlet increases, so the mass of water vapor in unit mass air decreases. Then the heat released by condensation of water vapor becomes less, which leads to the effect of relative humidity of HP inlet on refrigeration performance of gas wave refrigerator less.



(a)

(b)

Fig. 12 Comparison of pressure contour: (a) Without condensation-evaporation model (b) With condensation-evaporation model



(a) (b)

Fig. 13 Comparison of temperature contour: (a) With condensation-evaporation model (b) Without condensation-evaporation model

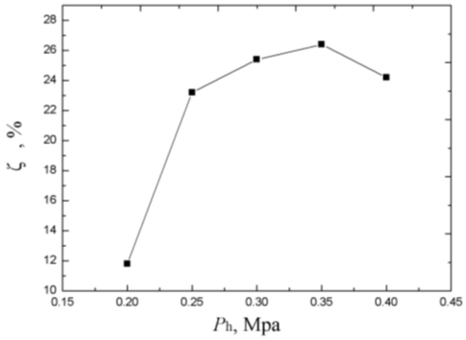


Fig. 14 Temperature drop at different pressure of high pressure inlet

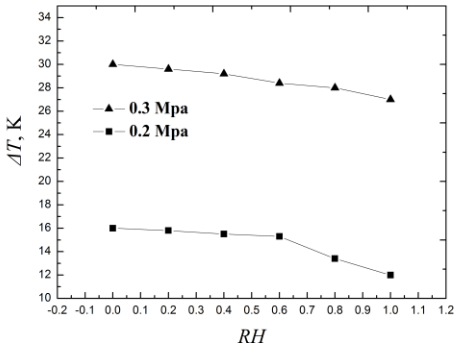


Fig. 15 Temperature drop under different relative humidity

IV. CONCLUSION

This paper concentrates on the condensation-evaporation in pressure oscillation tube. Numerical simulation of gas wave refrigerator using discrete phase model and condensation-evaporation model helps investigate the problem and comes to conclusions. Experiments also help the investigation go further.

(1) By means of numerical simulation with discrete phase model, it is found that when gas from high pressure inlet contains condensable component, there is not only condensation but also evaporation. Large droplets are more prone to pass through the interface between low temperature region and high temperature region even flow into high-temperature zone to evaporate in pressure oscillation tube.

(2) According to temperature contour of results of numerical simulation using condensation-evaporation numerical model, pressure waves caused by condensation could be discovered. In the result of numerical simulation using condensation-evaporation model, temperature of low temperature region in pressure oscillation tube is higher than that without the model.

When the gas from high pressure inlet contains saturated water vapor, with the increase of pressure of high pressure inlet, the percentage of reduction of temperature drop firstly rises then drops.

(3) Results of experiment show that with the increase of high pressure inlet relative humidity, the temperature drop between high pressure inlet and low temperature outlet decreases. With higher pressure of high pressure inlet, change trend of temperature drop becomes more gentle.

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