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Unsteady Condensation in Wave Rotor and its Effects on Refrigeration Performance

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Abstract—Refrigeration is a new field for wave rotor technology in recent years. Unsteady condensation in the wave rotor, which could affect the performance of the machine, is still a challenge. In this paper, the movement of condensed droplets in the wave rotor is investigated first and the existence of evaporation, which is responsible for the low efficiency of the wave rotor, is confirmed. Then characteristics of the flow field in the wave rotor involving condensation are obtained by numerical simulation using a condensation model that describes both nucleation and growth of droplets and an evaporation model that computes growth of droplets reversely. Finally, two important operating parameters, pressure and relative humidity of high-pressure inlet, are investigated to find out their influences towards the refrigeration performance under different condensation conditions by combining experiment results and numerical simulation. The results of this paper could help better understand unsteady condensation in wave rotor and improve design accuracy significantly.

Keywords—refrigeration, wave rotor, pressure waves, condensation, evaporation

I. Introduction

Wave rotor technology makes use of pressure energy of gas to realize energy transfer, which has the advantage of high isentropic efficiency. Wave rotor, shown in Fig. 1, composed of tubes with two open ends called pressure oscillation tubes, is the core component of the technology. Compared with the turbine that could also realize high isentropic efficiency energy transfer, wave rotor technology depends on the movement of pressure waves to work, so it could work at low rotational speed [1]. Early studies have shown that wave rotor technology can be used for pressurization and refrigeration [2].

In the study of wave rotor pressurization, since the 20th century, NASA has conducted experiments on wave rotor technology and gained significant experiences about the device design [3-8]. In recent years, Tokyo University applied wave rotor pressurization technology in small scale devices and summarized the characteristics of internal flow and heat transfer [9]. C-2 type of wave rotor pressurizer invented by the Institute of Mechanics of the Chinese Sciences Academy was put into industrial operation and achieved good performance [10]. Warsaw University of Technology investigated main flow features in wave rotor pressurizer utilizing PIV which helped the validation of CFD calculations [11]. As for the study of wave rotor refrigeration, in the 21st century, HU et al. proposed to use wave rotor technology to realize refrigeration and developed wave rotor refrigeration technology which could be used in areas such as dehydration of natural gas [12-13]. During the process of refrigeration, phase transformation generally happens. The ability to carry fluid is the key to the wave rotor refrigeration technology. Besides, in transporting natural gas, ethylene glycol or methanol is usually injected into the pipeline to avoid pipeline blockage due to freeze. Therefore the refrigeration device needs to carry the two-phase flow. In a wave rotor, the liquid could be carried by gas that flows out of the device through the outlet of the rotor. The wave rotor is an effective solution for getting rid of accumulated liquid which could corrode the device [14]. However, condensation will reduce the refrigeration performance.

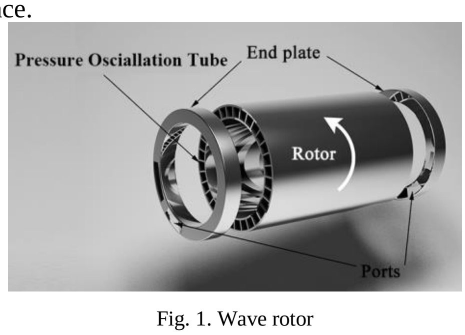


Fig. 1. Wave rotor

Over the years, researchers studied multiple aspects including pressurization and structure to improve the refrigeration performance of the wave rotor and made considerable progress [15-17]. However, there are only limited studies on condensation in the wave rotor. Nowadays, heat transmission characters of condensation have been studied and relevant conclusions have been obtained [18-20]. Based on this, condensation has been used to improve energy transformation performance and benefit industrial operations under certain conditions [21-22]. However, condensation flow has not been systematically well-studied. Traditional researches on condensation in high-speed flow mainly concentrate on supersonic nozzles [23-24]. Different from the traditional refrigeration device, the flow field in the wave rotor is unsteady and the condensable gas is in a non-equilibrium state most of the time, which makes the condensation process difficult to model and observe. Because of high-speed flow in the wave rotor, there are no effective experimental methods to help obtain internal condensation characteristics precisely. In the aspect of numerical simulation, previous researchers only confirmed the existence of condensation and neglected evaporation, making numerical simulation results not very accurate [25]. Usually, the design of wave rotor is based on the movement of pressure waves neglecting the influence of any phase transformation. Consequently, there is a big deviation between the practical and ideal refrigeration performance of the device. Therefore, it is necessary to carefully investigate condensation in the wave rotor.

This paper investigates particles movement to confirm the existence of evaporation, establishes condensation model and evaporation calculation model, which reversely uses the growth of droplets, to proceed numerical simulation to analyze internal flow that contains phase transformation in wave rotor. Experiments and numerical simulations are conducted to find out the influences of operating parameters on the refrigeration performance of the wave rotor.

II. MOVEMENT ANALYSIS OF PARTICLES

A. *Numerical model*

Fig. 2 shows a 2D ideal wave diagram in the wave rotor. It could explain the working principle of the wave rotor refrigeration technology. When the wave rotor is working, pressure oscillation tubes move upward periodically. Firstly, when high-pressure (HP for short) inlet connects a tube, HP gas injects and shock wave S1 appears. And then, shock wave S1 moves to the right compressing the original gas in the tube. At the same time, expansion waves also appear and expand HP gas. Then pressure oscillation tube starts to connect with high-temperature (HT for short) outlet, compressed gas in the tube discharges from HT outlet. Simultaneously, S1 reflects a series of expansion waves E1 at HT outlet, which makes the pressure and temperature of the gas in pressure oscillation tube lower. The gas that flows out of the HT outlet flows back to the pressure oscillation tube through medium-pressure (MP for short) inlet after exchanging heat with cool water. After that, the pressure oscillation tube leaves HP inlet, and another series of expansion waves E2 appears to expand the gas in the tube. The result is that the temperature and pressure of gas both decline. Finally, both sides of the pressure oscillation tube start to connect with low-temperature (LT for short) outlet and MP inlet, and the LT gas flows out through LT outlet pushed by differential pressure between LT outlet and MP inlet. So a cycle of work in the wave rotor is completed. To make sure LT gas could be completely expelled, the number and length of LT outlet and MP inlet should be increased.

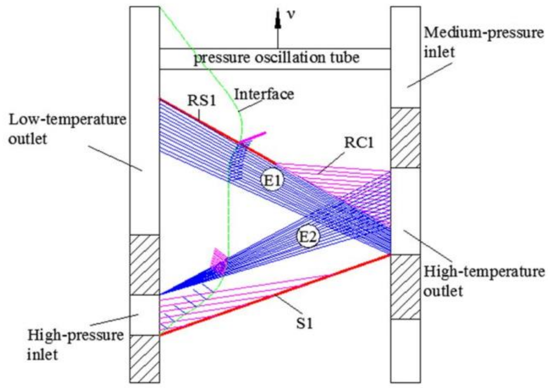


Fig. 2. Wave system in wave rotor

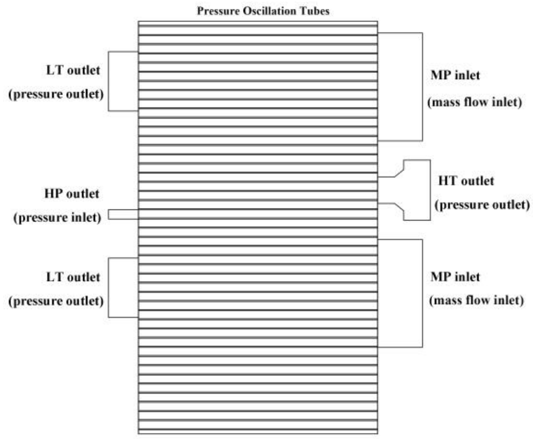
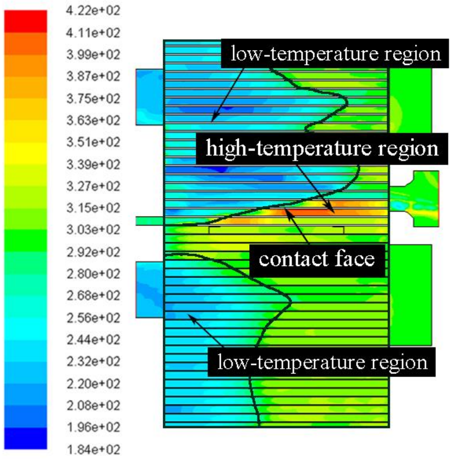


Fig. 3. 2D geometric model of the wave rotor

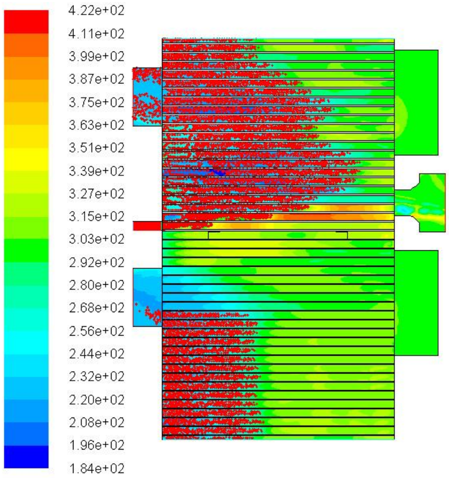
As for the geometric model of the wave rotor in CFD, calculation using the model needs high computing power and extended simulation time. Also, the ratio of length to width of pressure oscillation tube in the wave rotor is larger than 10, which is enough to regard the flow in the tube as plane flow. Based on this, our numerical simulation uses a 2D geometric model of the wave rotor shown in Fig. 3. The length and width of the pressure oscillation tube are set to be 400mm and 13mm, respectively. The velocity of the tube is set to be 33m/s upward, which is corresponding to the rotational speed of 3000rpm and the radial position of pressure oscillation tubes of 105mm, for matching the pressure waves. Fig. 3 shows the boundary conditions of inlets and outlets. The pressure of HP inlet is set from 0.2MPa to 0.4MPa and temperature 298K. The pressure of HT outlet and LT outlet is set to 0.1MPa. MP inlet is defined as the mass flow inlet to ensure its mass flow rate is equal to that of HT outlet. Flow temperature in MP inlet is defined as 298K. The fluid is defined as ideal air. After the grid independence test, grids size is set as 1.5*1.5 mm^2 and confirmed feasible numerical simulation. In order to simulate the periodical rotation of the wave rotor, the periodical boundary condition is used. The 2D geometric model has been confirmed valid by the previous study [26].

From the ideal wave diagram, when gas in HP inlet contains condensable components, condensation generally happens first when gas injects into the wave rotor. To figure out the path of droplets in the wave rotor, the DPM model could be used. In the previous study of droplets, the diameter of most condensed water droplets is not larger than 10μm [27]. Therefore, the diameter of the droplets is set to be 10μm, 1μm, and 0.1μm in this paper.

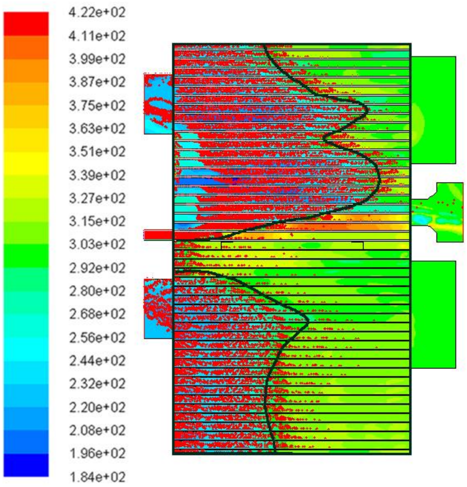
B. Analysis of particles movement



(a) Temperature contour (K) in wave rotor



(b) Path of particles with diameter 0.1μm in wave rotor



(c) Path of particles with diameter 10μm in wave rotor

Fig. 4 Results of numerical simulation including temperature (K) and particle path

When the pressure and temperature of the HP inlet are 0.4MPa and 298K, and the diameter of particle 10μm, Fig. 4 shows the results including the temperature contour and the path of droplets. The area below 298K is called the LT region; otherwise, it is called the HT region. From the temperature contour, it could be seen that a contact interface separates the LT region and the HT region.

As shown in Fig. 4, there are droplets getting through the contact interface and stay in the HT region with an increase of the diameter of droplets. As for droplets with 10μm diameter, significant amount of droplets are expelled through HT outlet. This proves that droplets in the wave rotor could evaporate after being heated. Besides, as shown in Fig. 4 (c), particles can't be fully exhausted out of the LT outlet after each work cycle of the wave rotor. There are droplets remain in the wave rotor in the next work cycle. The newly generated shock wave will compress these droplets and the droplets will evaporate. Therefore, when HP inlet gas contains condensable components, there is not only condensation in the wave rotor but also evaporation.

Like condensation, evaporation affects the mass flow of gas and the energy in the wave rotor, which inevitably affects wave movement and refrigeration performance of the wave rotor. Therefore, evaporation and condensation of droplets both need to be considered while analyzing the performance of the wave rotor.

III. INVESTIGATION ON PHASE TRANSFORMATION IN WAVE ROTOR

Because of rotation and high internal flow speed (>200m/s) in the wave rotor, phase transformation such as condensation and/or evaporation in the wave rotor is difficult to observe experimentally. Besides, the previous numerical model of wave rotor [25] involving phase transformation did not consider evaporation. Therefore, to better investigate the effects of phase transformation on the refrigeration performance of the wave rotor, we hereby establish a numerical phase transformation model that includes both condensation and evaporation, as well as the companion verification experimental platform.

A. Phase transformation model

The difficulty of establishing a numerical phase transformation model is to assure the transport of mass and energy between droplets and water vapor. Besides, condensation and evaporation need to be calculated separately. Theoretically condensation of droplets is divided into nucleation and growth of droplets and evaporation could be regarded as reverse growth of droplets. On the numerical model of phase transformation, the following assumptions are made. Velocity slip between droplets and gas is neglected, droplets volume and interaction are neglected, the internal temperature of droplets is homogeneous, and there are no foreign particles such as ionic and dust in the flow.

Therefore, the nucleation process could be regarded as homogeneous nucleation and nucleation rate J is as follows [28]:

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

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

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. ρ_v and ρ_l are respectively the density of gas and liquid. h_{lg} is the latent heat of the condensable component.

To describe the evaporation, the model is introduced by describing the growth of droplets reversely to thoroughly simulate the phase transformation process in the wave rotor for the first time. The Hertz-Knudsen equation is adopted for the droplet growth and evaporation model [29-30]:

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

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

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

Except for the droplet growth equation, calculation of evaporation also relies on the distribution of droplets. In previous researches on droplet distribution, Gaussian distribution, normal distribution, Gamma distribution, Beta distribution, and semi-normal distribution get taken into consideration [31]. In this paper, during the calculation of phase transformation, only the mass of fluid and quantity of droplets could be obtained, so the distribution of droplets is assumed uniform, which is:

$$f(r) = N / r_2 \tag{5}$$

where N is the quantity of droplets in unit mass of gas, r_2 is the largest radius of droplet which could be calculated by the mass of liquid and distribution equation.

B. *Experiment set up*

To confirm the validation of the numerical model and obtain the refrigeration performance of the wave rotor, our research group established the experimental system.

Fig. 5 shows the experimental system, and Fig. 6 shows the experimental process. HP air flows into two pipelines. In one pipeline HP air obtains saturated water vapor after flowing through the atomizer and swirl filter. In another pipeline, the air gets totally dried by an adsorption dryer. By controlling and mixing the mass flow of both pipelines, the relative humidity of HP inlet gas could be adjusted from 0 to 1. Moisture analyzer is set on HP inlet so relative humidity could be monitored. A heat exchanger is installed to make sure the gas flows out of the HT outlet could exchange heat with cold water before circulating back to MP inlet.

In pulse expansion wave tube [32], phase transformation including unsteady condensation and evaporation is closed to that in the wave rotor. So it could be used to verify the phase transformation model in this paper. LUO monitored the change of radius of droplets experimentally in the pulse expansion tube [27]. The result of CFD using condensation and evaporation model in this paper compared with experimental data by LUO is shown in Fig. 7. The changing trend of the droplet radius in the CFD result is consistent with the experiment, and the value of the droplet radius is closed to the measured value. The results indicate the phase transformation model established in this paper is feasible.

Fig. 5. Wave rotor experimental platform

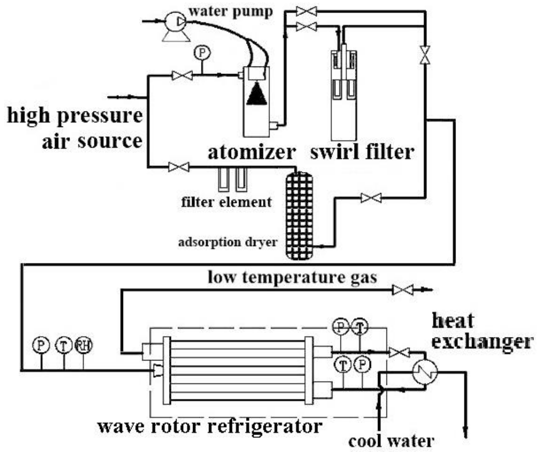


Fig. 6. Schematic diagram of experimental process

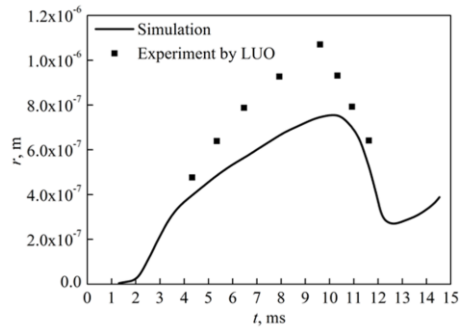


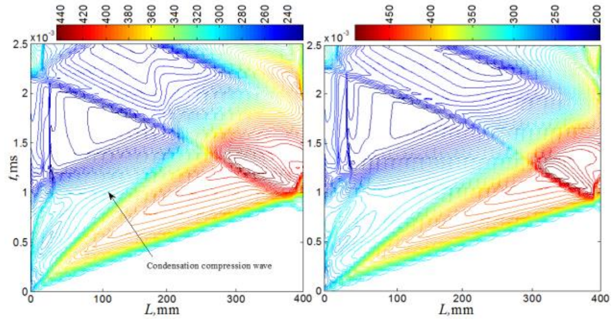
Fig. 7 Validation for evaporation and condensation model

C. *Investigation results*

First of all, the effect of phase transformation of wave rotor including condensation and evaporation is investigated using CFD.

As shown in Fig. 8, there are compression waves at the LT region of wave rotor with saturated water vapor in HP inlet. It can't be found when there is no vapor in the HP inlet. This phenomenon means the compression waves are caused by condensation, which releases the latent heat of water vapor and reduces the mass of water vapor. The compression waves affect the movement of subsequent expansion waves and deflect the wave system from the ideal one.

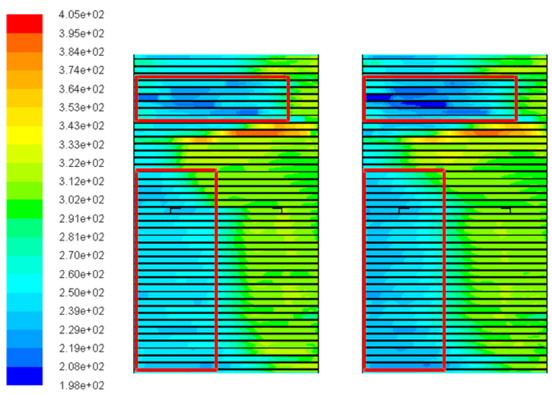
Fig. 9 shows the internal temperature distribution of the wave rotor in the situation that HP contains saturated water vapor and dry air. The temperature of LT regions of the wave rotor with saturated water vapor in HP inlet is higher than that with dry air in HP inlet. This result proves that heat released by condensation makes the temperature in the wave rotor rise and make the refrigeration performance of the wave rotor worse.



(a) (b)

Fig. 8 Comparison of temperature contour (K): (a) HP inlet contains saturated water vapor (b) HP inlet only contains dry air

Experiments are implemented to measure the effect of phase transformation on the refrigeration performance of the wave rotor. To obtain the effect rules of phase transformation on refrigeration performance, two operating parameters, pressure and relative humidity of HP inlet, are chosen as important parameters to investigate. Compared to dry air, when HP inlet contains water vapor, temperature drop will decline. To express this difference, the reduction percentage of temperature drop between HP inlet and LT outlet ζ is used.



(a) (b)

Fig. 9 Comparison of temperature contour (K): (a) With condensation-evaporation model (b) Without condensation-evaporation model

The relation of ζ to the pressure of HP inlet with the same relative humidity of HP inlet 1 from experiment and numerical simulation is shown in Fig. 10. Apparently, the value of ζ keeps positive, which means phase transformation does make the refrigeration performance of the wave rotor worse. With the increase of pressure of HP inlet, ζ decreases and the decrease rate of ζ to the pressure of HP inlet decreases. This could be explained that although higher pressure of HP inlet would generate more powerful expansion waves that could expand the mixture of air and water vapor from HP inlet more, increased heat released by condensation is less than the increased cold caused by higher pressure. When the pressure of HP inlet is high enough, which is able to make most of water vapor condense, released latent heat of water vapor is closed to its limitation. So the change rate of ζ to the pressure of HP inlet decreases with pressure of HP inlet.

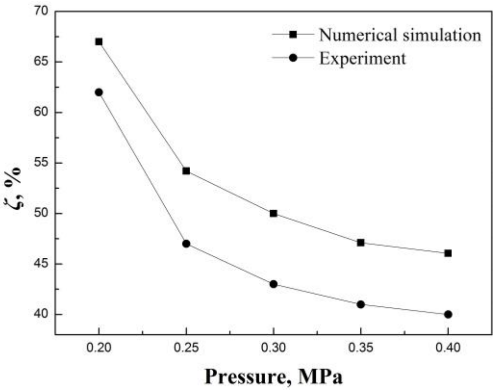


Fig. 10 ζ to pressure of HP inlet with relative humidity of HP inlet 1

The result confirms the correctness of the numerical simulations which could help obtain information about the flow field for analyzing the flow behavior and help provide a basis for controlling the path of droplets. In the future, the established numerical framework could be used to predict the refrigeration performance of the wave rotor.

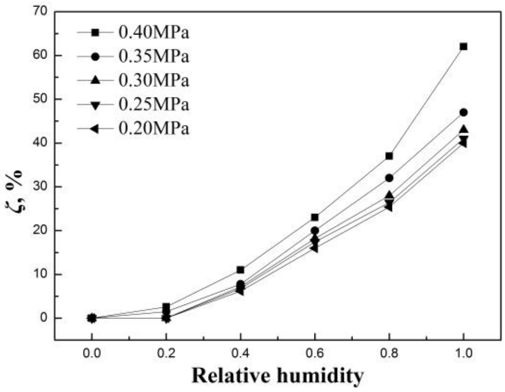


Fig. 11 ζ to relative humidity of HP inlet with different pressure of HP inlet

Fig. 11 shows the relation of ζ to the relative humidity of HP inlet with the pressure of HP inlet from 0.2MPa to 0.4MPa in experiment results. It can be seen that with the increase of relative humidity of HP inlet, ζ increases. With the same pressure of HP inlet, when the relative humidity of HP inlet is low, the partial pressure of water vapor is low which makes water vapor in the wave rotor hard to be expanded to a super-cooled state to condense, so the influence of condensation is small. Only when relative humidity is high enough to make partial pressure of vapor higher than the pressure of expanded gas, condensation happens.

From the reduction percentage of temperature drop between HP inlet and LT outlet it could be seen that the effect of condensation on the refrigeration performance of the wave rotor is large. Deeper analyses could help control condensation in the wave rotor which is meaningful for the wave rotor refrigeration field.

IV. CONCLUSION

This paper focuses on studying the phase transformation in the wave rotor using numerical simulations and experiments. The key results and conclusions are summarized as follows:

(1) By means of numerical simulations, it is found that large droplets are prone to flow through the contact interface to the high-temperature region in wave rotor and then evaporate which proves that phase transformation in wave rotor not only involves condensation but also evaporation. Phase transformation in wave rotor would bias the wave system from ideal one and worsen refrigeration performance.

(2) A computational model that describes both condensation and evaporation in unsteady flow is established. The model is confirmed to be valid by comparing with experimental results and could help predict the performance of wave rotor in the field for transporting wet gas.

(3) The results from both experiments and simulations show that, with the increase of pressure of HP inlet, reduction percentage of temperature drop between high-pressure inlet and low-temperature outlet declines and the decline rate of such percentage to the pressure of HP inlet decreases. With the increase of relative humidity of HP inlet, the percentage increases.

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