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Research Article

The Investigation on Heat Transfer Characteristics of Steam Condensation in Presence of Noncondensable Gas under Natural Convection

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The NHR-200 reactor in China adopts the noncondensable gas self-stabilizing control and the noncondensable gas used for pressure stabilization control can weaken steam condensation heat transfer in the integrated steam-gas pressurizer. A condensation experimental system was established and the heat transfer characteristics of steam-nitrogen and steam-argon condensation under natural convection had been investigated. The pressure ranged from 0.516 to 5.10 MPa. The distributions of nitrogen and argon in the steam/gas mixture were obtained in the experiments, and the results showed that nitrogen and argon were evenly distributed in the steam under different pressure, respectively. The effects of heat transfer temperature difference had also been investigated and it is found that the total heat transfer coefficient difference had little influence on the total condensation heat transfer coefficient. However, the steam condensation heat transfer coefficient decreased with the increase of the degree of supercooling of the wall. The condensation heat transfer coefficient was reduced by approximately 0.11 kW/(m^2·K) as the degree of supercooling of the wall changed from 14°C to 36°C. The condensation heat transfer coefficient also decreased with the mass/molar fraction of noncondensable gas increasing and a certain difference between the effect of the mass fraction of noncondensable gas and the effect of the molar fraction of noncondensable gas was discussed in this paper.

1. Introduction

Small- and medium-sized reactors (generally less than 300 MWe) have become one of the options for future power propulsion due to their high safety and reliability, low power density, short construction period, and so forth. The integrated reactor is one of the main types of small- and medium-sized reactors, such as VVER-300 and VK-300 reactors in Russia, SMART reactor in South Korea, SMR reactors in the United States, and NHR-200 reactor in China [1–3].

The NHR-200 reactor adopts the noncondensable gas self-stabilizing control, that is, the integrated steam-gas pressurizer is adopted and the noncondensable gas is used for the pressure stabilization control [4]. Extremely complicated thermohydraulic phenomena, such as the pressure transient, the stratification of noncondensable gas in the mixed gases, the heat and mass transfer at the steam-liquid interface, and steam condensation in presence of noncondensable gas on the wall, are involved in the steam-gas pressurizer and the existence of noncondensable gas makes these phenomena more complicated. The noncondensable gas will prevent the condensation of steam on the wall and greatly increases the condensation heat transfer thermal resistance, thereby reducing the steam condensation heat transfer coefficient [5].

A lot of experimental research on the effect of noncondensable gas on the steam condensation heat transfer characteristics has been done according to different working conditions and equipment. It is found that when the air concentration was 0.5%, the steam condensation heat transfer coefficient would decrease by 50% [6]. Uchida et al. selected air, nitrogen, and argon as the noncondensable gas and studied the effect of steam condensation heat transfer when the mass fraction of noncondensable gases varied in the range of 10% to 95% [7, 8]. Research on the effect of the inclination angle of the condensing surface on the steam condensation heat transfer in presence of noncondensable gases was conducted by Huhtiniemi and Corradini. It was found that the condensation heat transfer coefficient decreased by 15~25% when the inclination angle changed from 0° to 90°. Moreover, for the condition of low noncondensable gas concentration, the influence of the inclination angle of the condensing surface was small [9]. In order to investigate the condensation heat transfer capacity of steam on the inner surface of the AP600 pressure vessel, Anderson chose two sizes of vessels in the experiments and the noncondensable gases were air and helium, respectively. Experiments showed that when the molar fraction of helium was less than 35%, the influence of helium would be ignored. When the molar fraction of helium was higher than 35%, it would cause stratification of noncondensable gas in the steam [10]. It is well known that there are many factors affecting the steam condensation heat transfer by noncondensable gas, including the type and concentration of noncondensable gases [11–15], the degree of supercooling of condensing surface [16, 17], the inclination of condensing surface [18], and the flow rate of mixed gas [19], that is, with the increase of the concentration of noncondensable gas, the steam condensation heat transfer coefficient will decrease significantly. Different kinds of noncondensable gases have different effects on steam condensation heat transfer.

The studies also show that pressure is also an important factor affecting the condensation heat transfer of steam with noncondensable gases. In Dehbi's experiment, the noncondensable gases were air and helium, and the experimental pressures were 0.15 MPa, 0.3 MPa, and 0.45 MPa, respectively. It is found that the steam condensation heat transfer coefficient increased significantly with the increase of pressure and decreased slowly with the increase of the degree of supercooling of the wall [20]. Liu et al. conducted the condensation heat transfer experiments with noncondensable gas in the pressure range of 0.248~0.455 MPa and obtained the empirical correlations between the steam condensation heat transfer coefficient and pressure, steam molar fraction, and temperature difference [13]. Similarly, Li [16], Zhang [21], and others also had obtained the empirical correlations of steam condensation heat transfer related to pressure. The experimental pressure of Kim et al. [5] was 0.1~2.0 MPa, and the noncondensable gas was nitrogen. It is proved that nitrogen was uniformly distributed in the steam at each pressure according to the experimental results.

In summary, the investigations on steam condensation heat transfer in presence of noncondensable gas are mainly focused on the forced convection and low-pressure conditions. There are barely condensation studies on natural circulation and high-pressure conditions. For the experimental studies, the pressure in the reported condensation experiments under natural convection is confined within 2.0 MPa. Therefore, the investigations on heat transfer characteristics of steam condensation in presence of noncondensable gas under natural convection are conducted and an experimental system is established in this paper. The effects of nitrogen and argon on the steam condensation have been investigated and the pressure ranges from 0.516 to 5.10 MPa. Some factors, such as the distribution of noncondensable gas in the steam, heat transfer temperature difference, the mass fraction, and molar fraction of noncondensable gas, have been studied in the experiments under high pressure in this paper.

2. Experimental System and Data Analysis

2.1. Experimental System. As shown in Figure 1, a steam condensation experimental system has been built and mainly consists of four parts: the primary loop, the secondary cooling loop, the vacuum and gas transmission system, and the data acquisition and control system. During the experiments, steam will be generated in the primary vessel by heating water and enter the noncondensable gas space of the vessel through the steam-liquid interface. Then, steam will be condensed on the outer surface of the condensing section due to the wall subcooling.

The coolant flows in the annular channel inside the condensing section and absorbs the condensation latent heat due to steam condensation on the vertical wall of the stainless steel cylinder. The condensing section consists of a 1.669 m long and 76 mm outer diameter, stainless steel cylinder positioned centrally inside the primary vessel. The condensing section consists of an inner tube, 34 mm outer diameter, and an outer condensing tube, 60 mm inner diameter. As shown in Figure 2, the wall temperature of the condensing section can be measured in the experiments and five thermocouple wires (TW1-TW5) are welded on the outer surface of the tube by the interval of 300 mm. And five sheathed K-type thermocouples (T201-T205) are fixed at the corresponding position in the annular channel of the tube to obtain the coolant temperature.

The primary vessel is made of stainless steel with 3.66 m long and 0.4 m inner diameter. The vessel is fully insulated so that steam condensation will only occur on the stainless steel cylinder. The steam is generated at the bottom of the vessel by a set of electrical heaters with 0~60 kW power. The primary vessel is maintained vacuum prior to the condensation experiments and the noncondensable gas is injected into the vessel by the vacuum and gas transmission system. Nitrogen and argon are chosen as the noncondensable gas and investigated in the experiments. The parameters, such as pressure, differential pressure, temperature, and mass flow rate, are measured and acquired in the experiments.

2.2. Data Analysis. The temperature, which consists of the wall temperature of the condensing section, the steam/noncondensable gas bulk temperature, and the coolant temperature of the secondary cooling loop, is measured in the experiments. The pressure in the primary vessel and in the secondary cooling loop is also obtained. It is assumed that the steam shares the same temperature with the noncondensable gas in the primary vessel during the

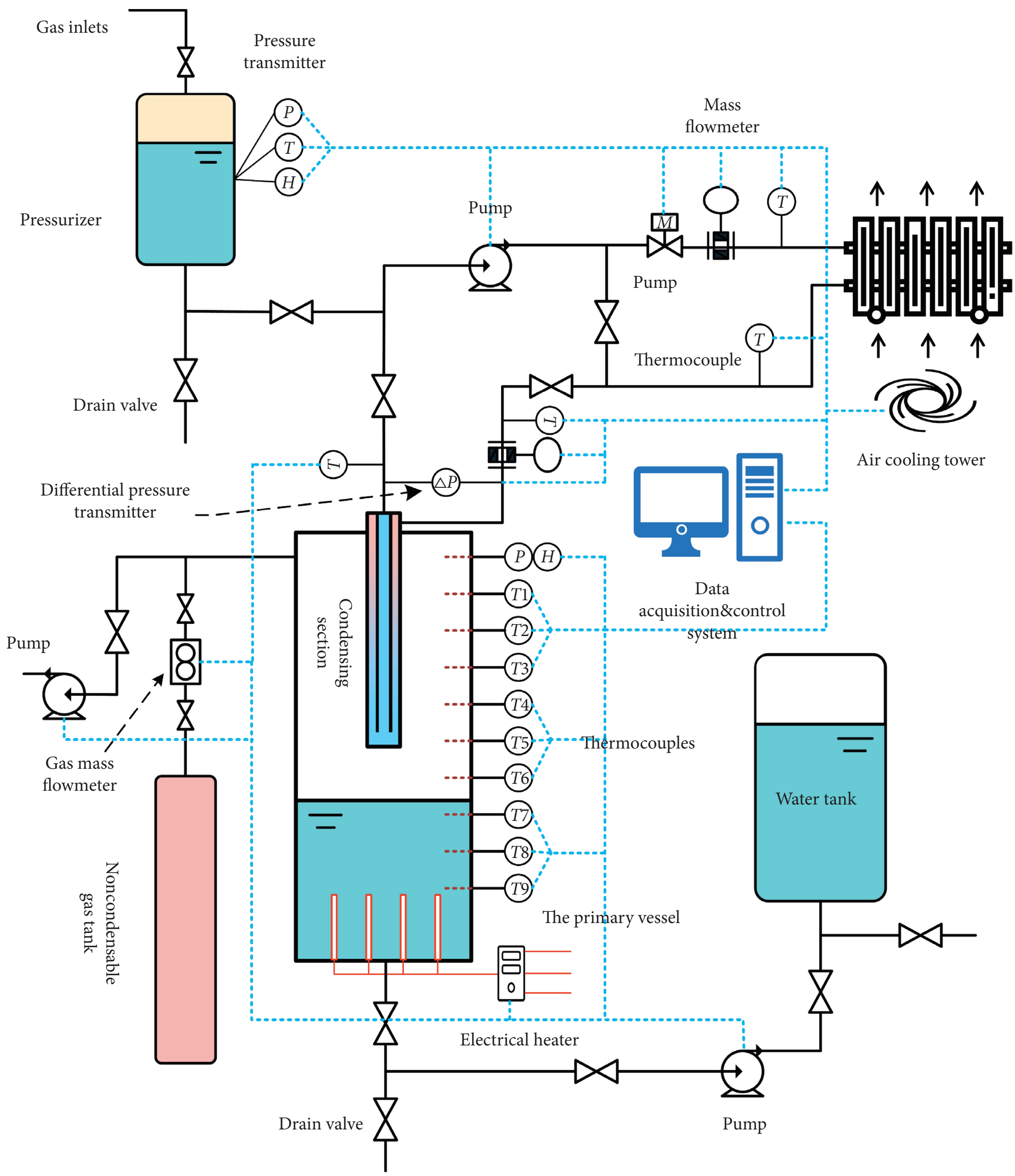


Figure 1: The steam condensation experimental system under natural convection.

experiments. What is more, the radial temperature difference of the steam/gas mixture in the vessel is neglected.

Due to the presence of noncondensable gas, the measured steam temperature is less than the steam saturation temperature corresponding to the current bulk pressure. So, the axial steam temperature profile can be used to figure out the noncondensable gas concentration variation in the axial direction [20]. Assuming steam is always at saturation at any temperature, the steam partial pressure in the steam/gas mixture can be easily given by

$$P_n = P_t - P_s(T_x). \quad (1)$$

Depending on Dalton's law of partial pressure [22], the ratio of the mass of noncondensable gas to the mass of steam is

$$\frac{m_n}{m_s} = \frac{P_n}{P_s(T_x)} \cdot \frac{M_n}{M_s} = \frac{P_t - P_s(T_x)}{P_s(T_x)} \cdot \frac{M_n}{M_s}. \quad (2)$$

The mass fraction of the noncondensable gas $W_n(x)$ is defined as

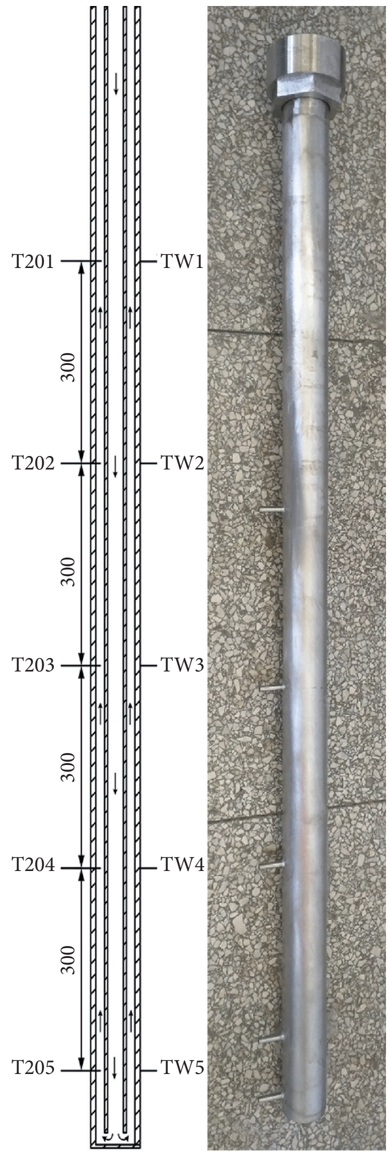


Figure 2: Temperature measurements of the condensing section.

$$W_n(x) = \frac{m_n}{m_n + m_s} = \frac{(m_n/m_s)}{1 + (m_n/m_s)}. \tag{3}$$

Therefore,

$$W_n(x) = \frac{P_t - P_s(T_x)}{P_t - P_s(T_x)(1 - (M_s/M_n))}. \tag{4}$$

In the same way, the molar fraction of noncondensable gas $X_n(x)$ can be obtained as

$$X_n(x) = \frac{P_n Z_s}{P_n Z_s + P_s(T_x) Z_n} = \frac{P_t - P_s(T_x)}{P_t - P_s(T_x)(1 - (Z_n/Z_s))}, \tag{5}$$

where Z is the compressibility factor of gas. Due to the high-pressure condition in the experiments, the compression effect of high pressure on the steam/gas is obvious and should be taken into account. Z can be given by the pressure and temperature.

The effect of the curvature of the condensing cylinder should be also taken into account. The heat transfer on the cylinder surface can be enhanced compared to the flat plate surface. However, the outer diameter of the condensing cylinder in the experiments is 76 mm, far greater than the thickness of the condensate film. Therefore, the enhancement of curvature of the condensing cylinder on steam condensation is ignored.

For a length L of the condensing cylinder, the average condensation heat transfer coefficient of steam, $\overline{h_L}$, and the heat transfer rate of steam condensation, Q, are defined as follows [23]:

$$\overline{h_L} = \frac{\dot{M}(h_{\text{out}} - h_{\text{in}})}{\pi D_o L(\overline{T_\infty} - \overline{T_w})}, \qquad Q = \dot{M}(h_{\text{out}} - h_{\text{in}}). \tag{6}$$

What is more, the steam condensation rate is calculated as

$$\overline{h_L} = \frac{\dot{M}(h_{\text{out}} - h_{\text{in}})}{\pi D_o L(\overline{T_\infty} - \overline{T_w})}. \tag{7}$$

3. Results and Discussion

3.1. The Distribution of Noncondensable Gas in the Steam/Gas Mixture. The distribution of noncondensable gas in the mixture space is a vital factor affecting the heat transfer characteristics of steam condensation. Assume that the concentration of noncondensable gas in the radial direction is constant and the difference in the concentration of noncondensable gas in the axial direction is only taken into account. Usually, the general distribution of noncondensable gas in steam can be judged by the molar mass of noncondensable gas; that is, the lighter gas (the molar mass of gas is less than the molar mass of steam) is mainly distributed in the upper space due to the effect of buoyancy. The heavier gas (the molar mass of gas is larger than that of steam) is mainly distributed in the lower space.

However, in the condensation experiments (the experimental conditions of condensation are shown in Table 1), due to the continuous generation of steam in the liquid space, the steam with a certain initial velocity will carry parts of noncondensable gas upward during the ascent, which makes the distribution of noncondensable gas in the steam more uniform to a certain extent [24, 25].

Nitrogen and argon were selected and the distributions of nitrogen/argon in the mixture space under natural convection were studied in the experiments, as shown in Figures 3 and 4.

According to the pressure and temperature in the axial direction in the primary vessel, the mass fraction of nitrogen/argon can be calculated. The distributions of nitrogen are illustrated in Figure 3. It is indicated that the mass fraction of nitrogen in the axial direction is relatively evenly distributed as the primary pressure increases from 0.517 to 5.10 MPa and

Table 1: Experimental conditions of steam condensation in the presence of nitrogen/argon.

Parameter	Value
Pressure in the primary vessel/MPa	0.516~5.10
Temperature in the primary vessel/°C	80~267
Pressure in the coolant loop/MPa	0.40~3.2
Temperature difference between the inlet and outlet of the condensing section/°C	10~20
Mass flow rate of coolant/t/h	0~8.5
Mass fraction of N_2/Ar	10%~85%

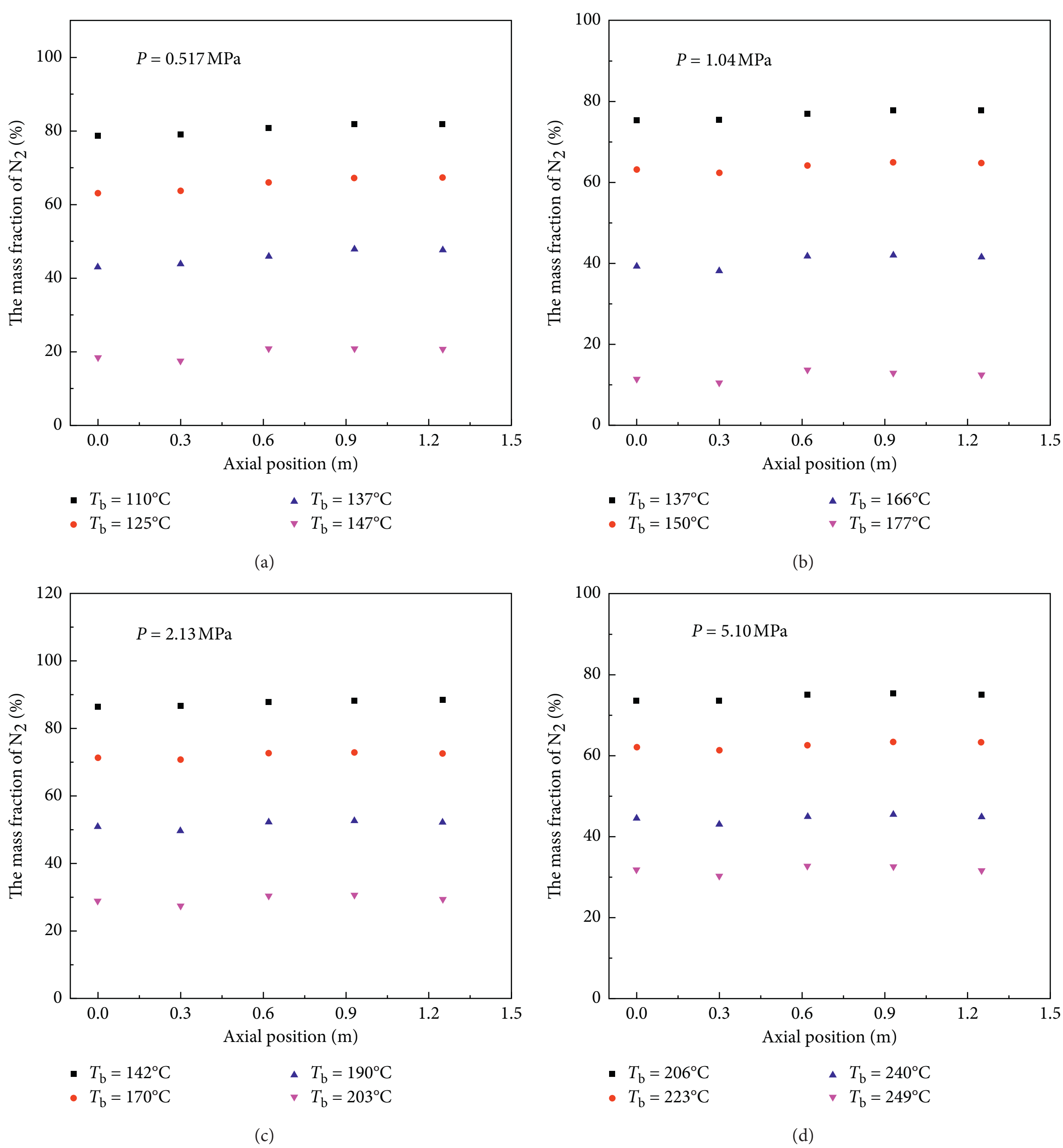


Figure 3: The distributions of N_2 in the axial direction. (a) $P = 0.517$ MPa. (b) $P = 1.04$ MPa. (c) $P = 2.13$ MPa. (d) $P = 5.10$ MPa.

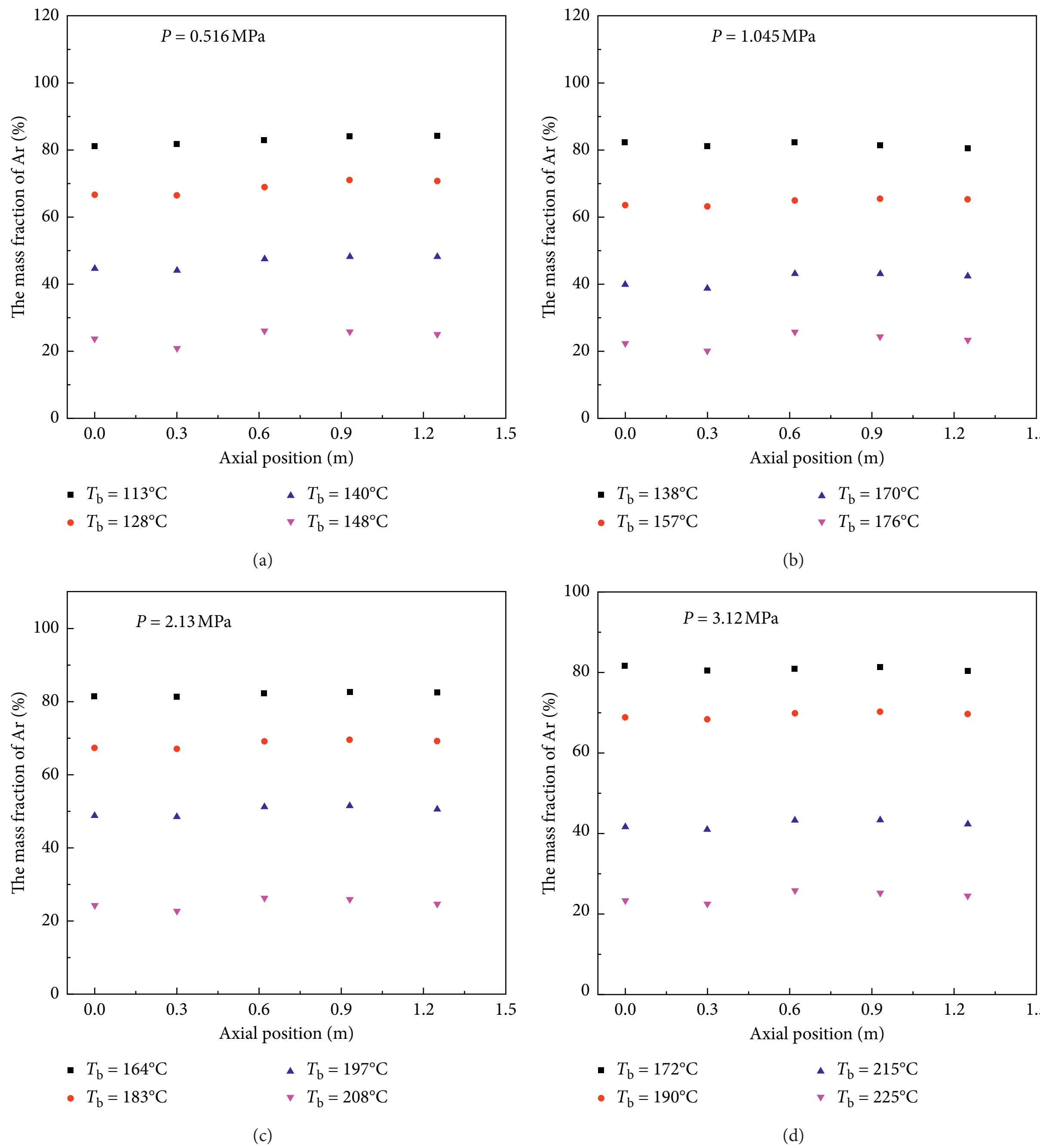


Figure 4: The distributions of Ar in the axial direction. (a) $P = 0.516$ MPa. (b) $P = 1.045$ MPa. (c) $P = 2.13$ MPa. (d) $P = 3.12$ MPa.

the gas temperature is from 110°C to 249°C. The differences in the mass fraction of nitrogen are little and have similar trends when the axial distance increases. When the primary pressure is 0.517 MPa and the steam temperature is 110°C, the mass fraction of nitrogen slightly increases from 78.62% to 81.07% along the axial direction. When the axial position changes from 0 to 0.62 m, the mass fraction of nitrogen increases from 78.62% to 80.68%. However, the mass fraction of nitrogen stays around 81% with the axial position of 0.62 to 1.251 m. The mass fraction of nitrogen in the axial direction shows the same change law as the steam temperature is 125°C, 137°C, and 147°C, respectively.

The distributions of nitrogen also have the same characteristics in the axial direction under other pressure conditions, such as 1.04 MPa, 2.13 MPa, and 5.10 MPa. And the differences in mass fraction along the axial direction are getting smaller with the increase of pressure. The reason for these is that the smaller the axial position distance is, the closer it is to the lower liquid space. As the system is in a steady state during the condensation experiments, the steam is continuously generated in the liquid space and transferred into the steam/gas mixture space, so the closer to liquid is, the larger the steam mass fraction is and the smaller the corresponding mass fraction of nitrogen is.

In general, the difference in nitrogen mass fraction along the axial direction is small and can be ignored. The spatial distribution of nitrogen is relatively uniform, and there is no obvious stratification phenomenon in the steam/gas mixture. This is the result of the natural circulation flow of steam in space and the downward flow trend of nitrogen because its molar mass is slightly larger than that of steam.

The distributions of argon are illustrated in Figure 4 and have similar characteristics to the distributions of nitrogen. Although the molar mass of argon is larger than steam, the steam, generated in the liquid space, with a certain initial velocity carries parts of argon upward and results in relatively uniform distributions of argon in the axial direction.

3.2. Effect of Heat Transfer Temperature Difference on Steam Condensation Heat Transfer in Presence of Noncondensable Gas. During the experiments, the primary pressure and temperature vary with the operating conditions' parameters such as the concentration of noncondensable gas, while the change of the secondary loop temperature relatively lags behind, which leads to great difficulties in controlling the condensation experiments. Therefore, the control scheme of the total heat transfer temperature difference between the primary and secondary loops varying with the concentration of noncondensable gas is adopted in the experiments. Before investigating the effect of noncondensable gas on the heat and mass transfer of steam condensation, it is necessary to determine the influences of the total heat transfer temperature difference between the primary and secondary loops on the heat transfer of steam condensation with noncondensable gas.

When discussing the influences of the total heat transfer temperature difference on the steam condensation heat transfer, a set of experimental conditions were selected for discussion; that is, the total pressure of the system was approximately 0.520 MPa and nitrogen with a mass fraction of 47% was chosen. The main control scheme was that the frequency of the pump in the secondary loop was kept as constant as possible, and the system automatically adjusted the total temperature difference between the primary and secondary loops by adjusting the heating rod power to maintain the total pressure in the primary loop at about 0.520 MPa, and the nitrogen mass fraction was also maintained at about 47%.

When the experimental system reached a steady state and the frequency of the pump in the second loop was kept unchanged, at first, because the temperature in the secondary loop was the lowest, the total heat transfer temperature difference was the largest. The primary loop was always maintained at a steady state over time, while the second loop was gradually heated by the primary loop due to the heat transfer between the primary and secondary loops. The total heat transfer temperature difference decreased gradually over time.

The range of the total heat transfer temperature difference is 41~110°C, and the temperature difference between the inlet and outlet of the condensing section was 5~10°C. The pressure and flow rate of the secondary loop are shown in Figure 5.

It is indicated that the inlet and outlet temperature of the condensing section gradually increases with the decrease of the total heat transfer temperature difference in Figure 5. What is more, the coolant of the secondary loop is gradually heated by the primary loop, which gradually leads to an increase of the pressure in the secondary loop. And the physical parameters of coolant in the secondary, such as the density and the viscosity, change accordingly and the coolant flow rate decreases. It is because that the total heat transfer temperature difference and the heat transfer of the steam condensation decrease gradually, resulting in the gradual decrease of the heat taken away by the secondary loop, while the frequency of the circulation pump of the secondary loop remains unchanged. The automatic control scheme was adopted in the experiments; according to the conservation of energy, the coolant circulation flow rate of the secondary loop decreased gradually.

As shown in Figure 6, when the pressure is 0.520 MPa and the mass fraction of nitrogen is 47%, the total heat transfer coefficient of steam condensing on the vertical wall is about 0.215 kW/(m^2·K), and the heat transfer coefficient remains basically unchanged with the increase of the total heat transfer temperature difference. When the total heat transfer temperature difference is less than 70°C, the total heat transfer coefficient is always slightly larger than 0.215 kW/(m^2·K). And then the total heat transfer coefficient is slightly less than 0.215 kW/(m^2·K) as the total heat transfer temperature difference is greater than 70°C. This is because when the total heat transfer temperature increases, the heat transfer in the steam condensation is enhanced, and the amount of steam condensing on the vertical wall increases subsequently, resulting in the thickening of the condensate film, which increases the heat transfer resistance, and the total heat transfer coefficient will decrease.

However, the thickness of the condensate film in the experiments is far smaller than the diameter of the condensing section, and the effect of the increase in the thickness of condensate film on the total heat transfer resistance is very limited. Therefore, as the total heat transfer temperature difference varies from 41°C to 110°C, the change of the total heat transfer coefficient is within 0.016 kW/(m^2·K), which can be tolerated.

The steam condensation heat transfer has been paid more attention and closely related to the condensation heat transfer temperature difference in the experiments. The condensation heat transfer temperature difference refers to the temperature difference between the bulk temperature in the primary loop and the temperature of the vertical condensation wall. Usually, the bulk temperature in the primary loop is considered to be equal to the steam saturation temperature, so the condensation heat transfer temperature difference is also called the degree of supercooling of the wall, which is controlled by the flow rate of coolant in the secondary loop in the experiments.

It is known that the degree of supercooling of the wall is a vital parameter affecting the steam condensation on the wall,

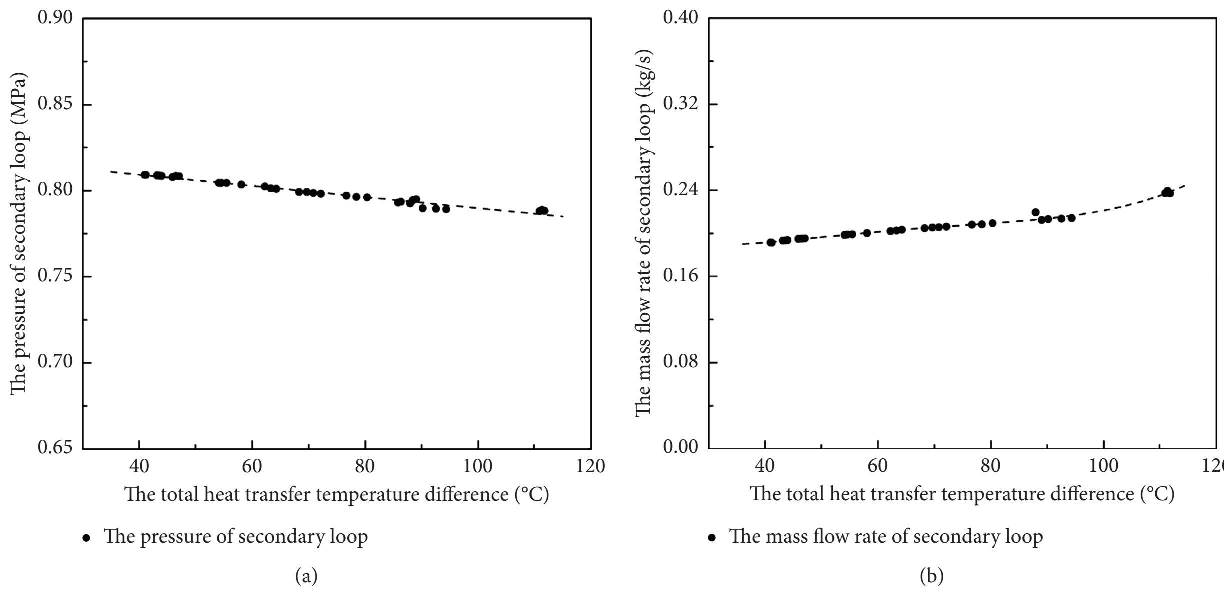


Figure 5: The pressure and flow rate of the secondary loop. (a) The pressure in the secondary loop. (b) The flow rate of the secondary loop. (c) The inlet and outlet temperature of the condensing section.

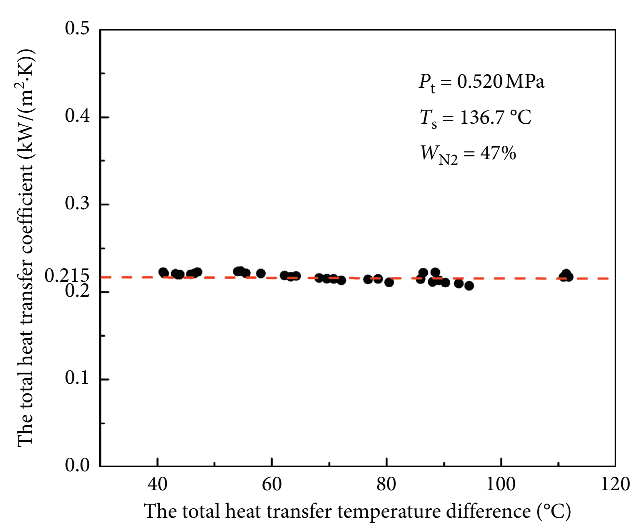


Figure 6: The effect of total heat transfer temperature difference on steam condensation.

and its influence on the heat transfer coefficient of steam condensation also needs to be determined.

As shown in Figure 7, it is obvious that the heat transfer coefficient of steam condensation decreases with the increase of the degree of supercooling of the wall as the primary pressure is 0.520 MPa and the mass fraction of nitrogen is 47%. When the degree of supercooling of the wall is approximately 14°C, the steam condensation heat transfer coefficient is 0.649 kW/(m^2·K). While the steam condensation heat transfer coefficient is 0.539 kW/(m^2·K) as the degree of supercooling of the wall is about 36°C. The curve of steam condensation heat transfer coefficient with the degree of supercooling of the wall is close to the polynomial function.

In conclusion, the total heat transfer temperature difference has little influence on the total heat transfer coefficient in the experiments. Therefore, in order to facilitate the control, the variable temperature difference control scheme was adopted in the experiments; that is, the parameters such as the temperature and pressure of the primary loop are adjusted by changing the flow rate of coolant in the secondary loop and the flow into the air cooling tower. What is more, the degree of supercooling of the wall is an important factor affecting the heat transfer of steam condensation on the wall. With the increase of the degree of supercooling of the wall, the steam condensation heat transfer coefficient decreases gradually. Therefore, the degree of supercooling of the wall should be controlled in a very small range as far as possible during the experiments.

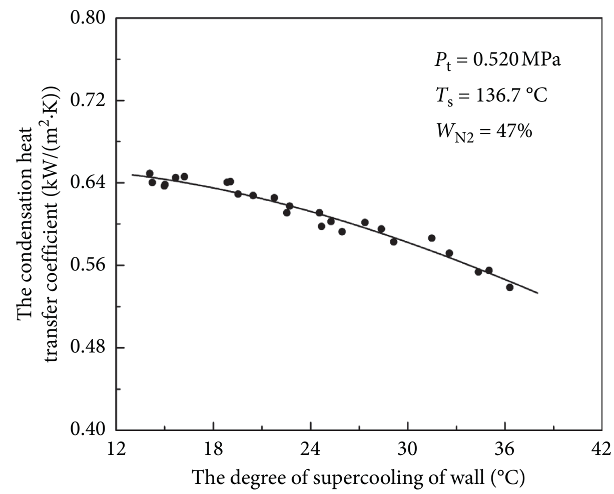


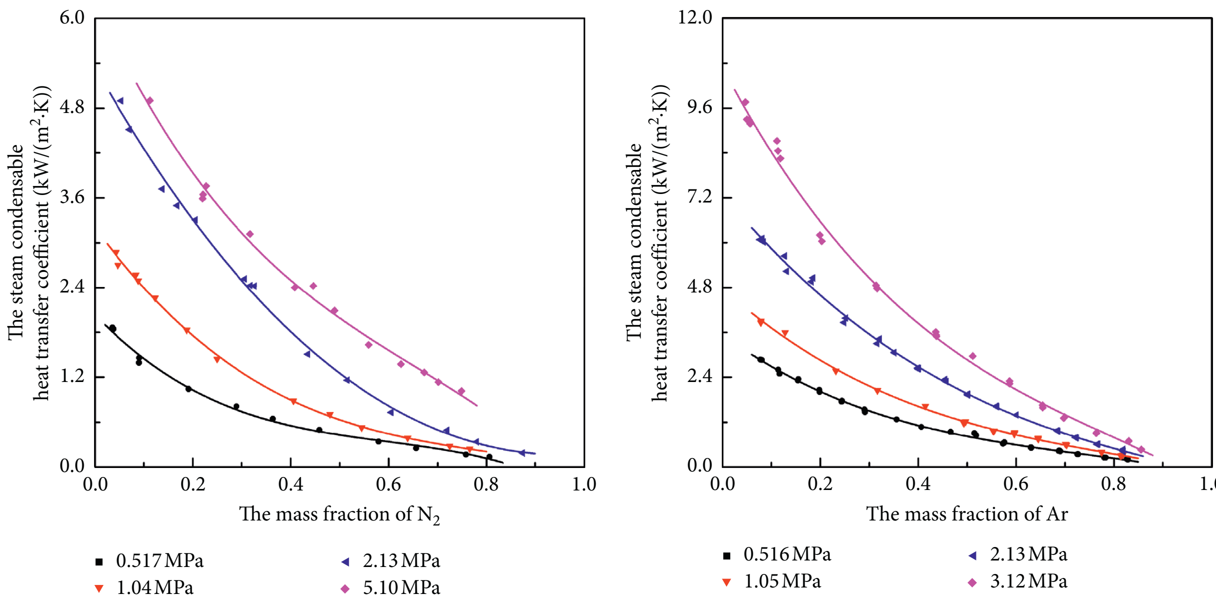
FIGURE 7: The effect of degree of supercooling of the wall on steam condensation.

3.3. Effect of Noncondensable Gas on Steam Condensation Heat Transfer. By forming a thin layer of noncondensable gas between the steam/gas mixture and the condensate film, the noncondensable gas prevents the steam from being close to the condensing surface and forms a large thermal resistance, which weakens the heat and mass transfer in the steam condensation. Therefore, the concentration of noncondensable gas is one of the most important factors affecting the heat and mass transfer in steam condensation. The more the concentration of the noncondensable gas is, the thicker the layer of the noncondensable gas is formed, resulting in greater thermal resistance. Usually, two parameters, mass fraction and molar fraction, are used to describe the concentration of noncondensable gas.

3.3.1. Effect of the Mass Fraction of Noncondensable Gas. As shown in Figure 8, for various pressure conditions, the steam condensation heat transfer coefficient on the vertical wall decreases with the increase of the mass fraction of N_2/Ar. In Figure 8(a), when the pressure is 0.517 MPa and the mass fraction of N_2 is 9.03%, the condensation heat transfer coefficient is 1.393 kW/(m^2·K). And as the mass fraction of N_2 increases to 75.76%, the condensation heat transfer coefficient is reduced to 0.165 kW/(m^2·K). For the other pressure conditions, the condensation heat transfer coefficients show the same law of change. In Figure 8(b), the condensation heat transfer coefficients under different pressure in the presence of Ar are given and have a similar feature with those in the presence of N_2.

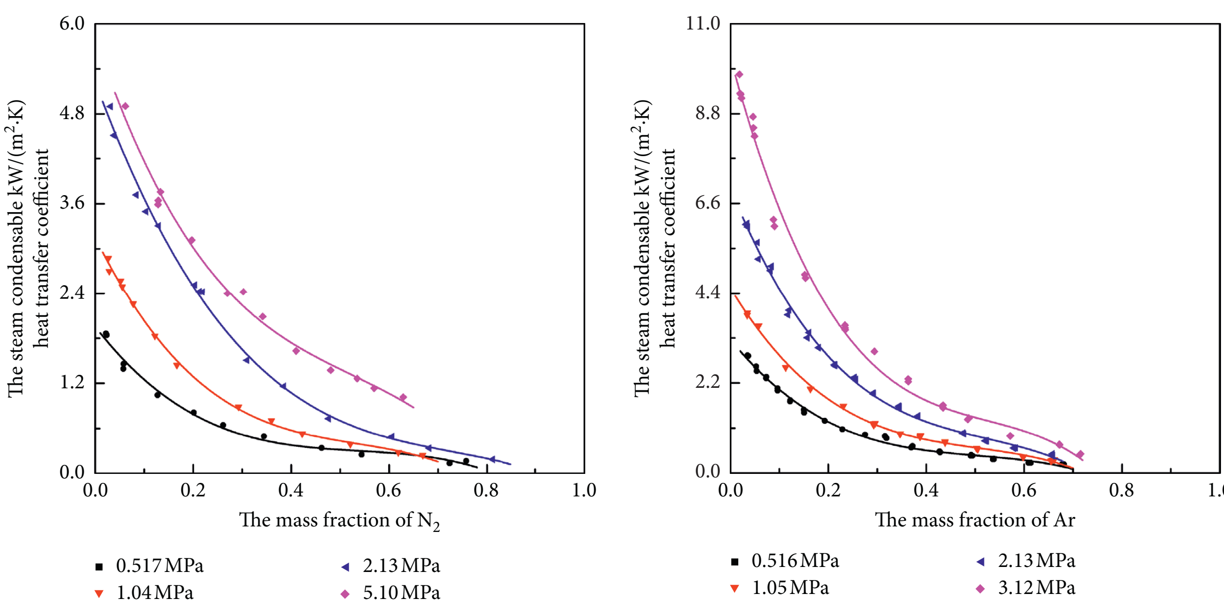
3.3.2. Effect of the Molar Fraction of Noncondensable Gas. As shown in Figure 9, the steam condensation heat transfer coefficient on the vertical wall also decreases as the molar fraction of N_2/Ar increases for various pressure. For example, it is indicated that the steam condensation heat transfer coefficient is 4.51 kW/(m^2·K) for the pressure of 2.13 MPa and the N_2 molar fraction of 3.83% in Figure 9(a). However, when the molar fraction of N_2 increases to 81.2%, the associated steam condensation heat transfer coefficient decreases to 0.187 kW/(m^2·K). And in the cases of other pressure or the noncondensable gas being Ar, the steam condensation heat transfer has the same law of change. It is obvious that the effects of the molar fraction of the noncondensable gas are consistent with the effects of the mass fraction of the noncondensable gas on the steam condensation heat transfer coefficient on the vertical wall.

3.4. Effect of the Pressure on Steam Condensation Heat Transfer. The effect of pressure on the heat transfer of steam condensation with nitrogen is shown in Figure 10. It is indicated that the heat transfer coefficients of steam condensation increase with the increase of pressure; namely, the pressure can enhance the heat transfer of steam condensation. For instance, when the mass fraction of nitrogen is 20%, the heat transfer coefficient is 0.757 kW/(m^2·K) for pressure 0.214 MPa and 4.26 kW/(m^2·K) for pressure 5.12 MPa. What is more, the curves of heat transfer coefficient with pressure have a larger slope in the low-pressure region, and the slope decreases with the increase of pressure.



(a) (b)

Figure 8: Effects of the mass fraction of noncondensable gas. (a) N_2. (b) Ar.



(a) (b)

Figure 9: Effects of the molar fraction of noncondensable gas. (a) N_2. (b) Ar.

That is, the enhancement of pressure on steam condensation heat transfer is obvious in the low-pressure region, and its enhancement weakens gradually with the increase of pressure. It is also obtained that the curves of steam condensation heat transfer coefficient with pressure are very close to the logarithmic function curves when the mass fraction of nitrogen is less than 50%. However, the curves begin to be irregular when the mass fraction of nitrogen is from 50% to 80%.

Figure 11 shows the effect of pressure on the heat transfer of steam condensation with argon. The pressure has a similar enhancement on steam condensation for argon with that for nitrogen. It is also found that the curves of steam

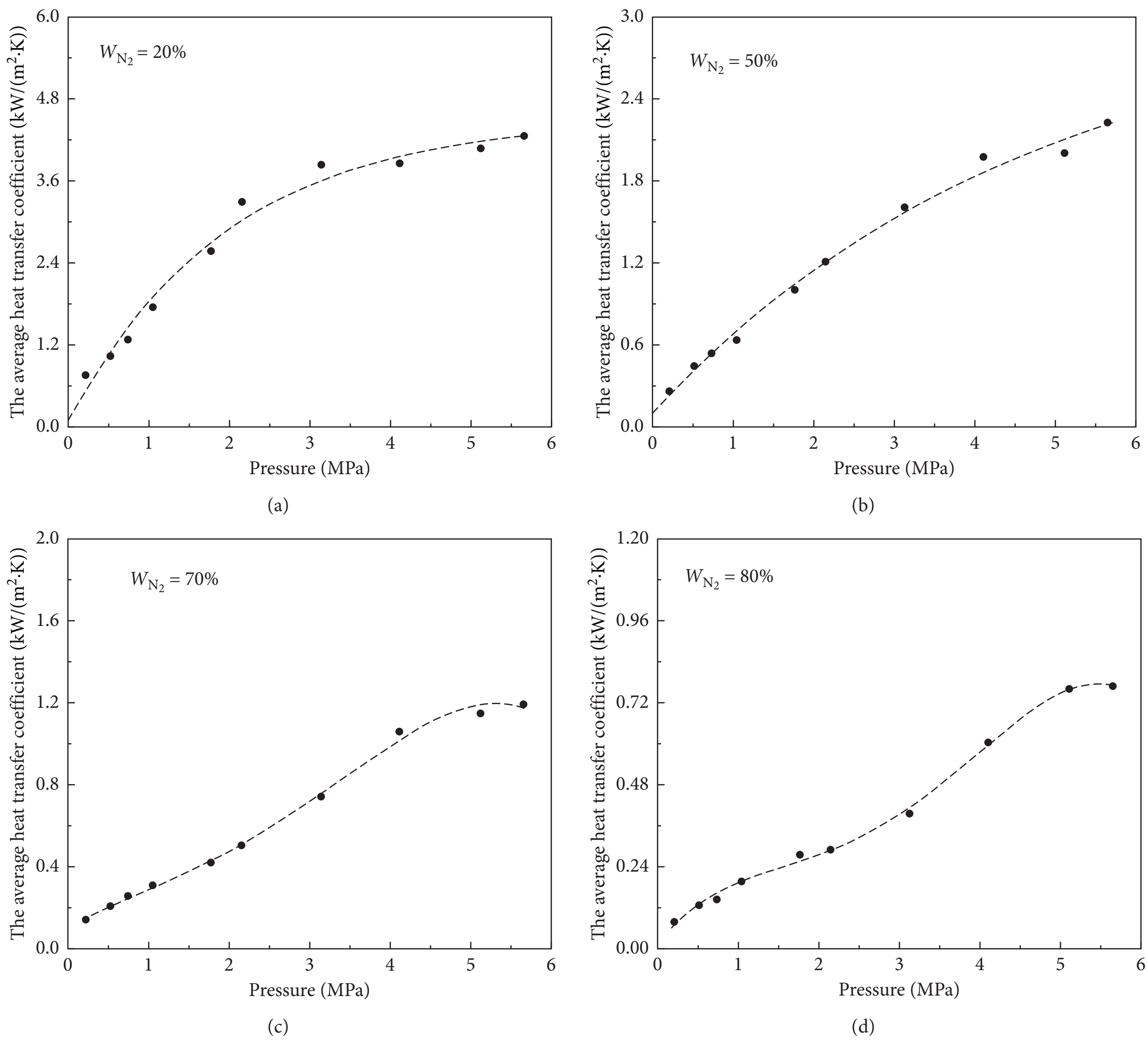


Figure 10: Effect of pressure on the steam condensation with N_2. (a) $W_{N2} = 20\%$. (b) $W_{N2} = 50\%$. (c) $W_{N2} = 70\%$. (d) $W_{N2} = 80\%$.

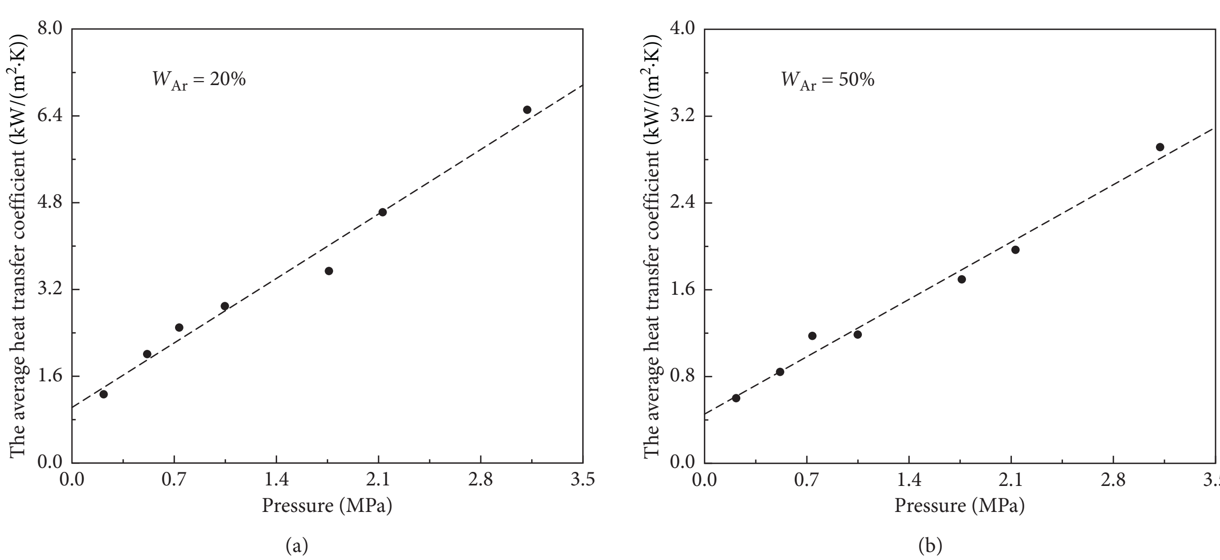
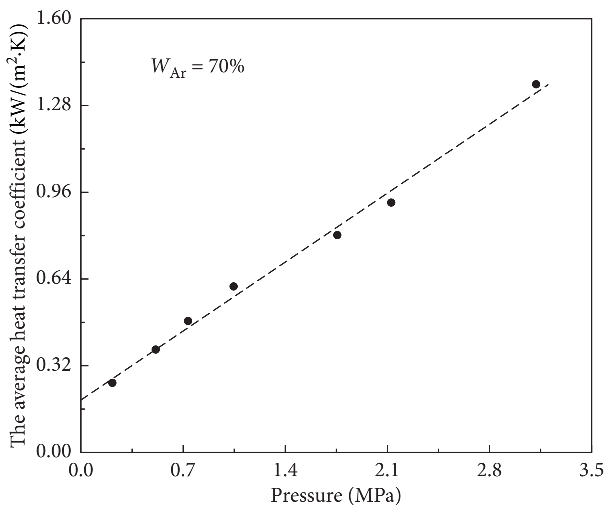
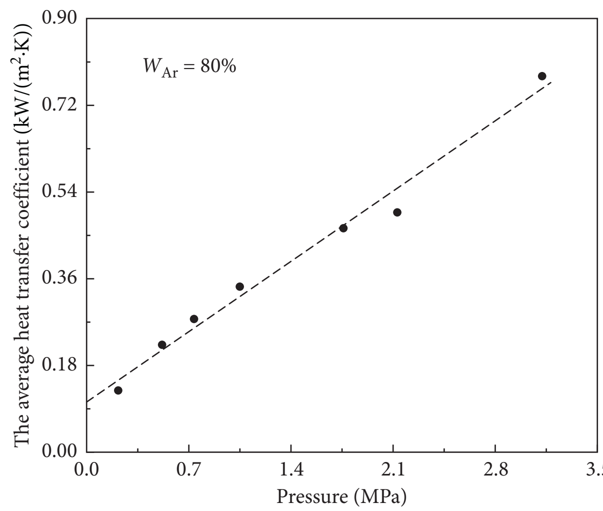


Figure 11: Continued.



(c)



(d)

Figure 11: Effect of pressure on the steam condensation with Ar. (a) $W_{Ar} = 20\%$. (b) $W_{Ar} = 50\%$. (c) $W_{Ar} = 70\%$. (d) $W_{Ar} = 80\%$.

condensation heat transfer coefficient with pressure are very close to the linear function curves with the pressure from 0.2 to 3.1 MPa. And, the curves are very close to the linear function curves when the mass fraction of argon is from 20% to 80%, which is different from those with nitrogen.

4. Conclusions

An experimental system had been established to investigate the heat transfer characteristics of steam condensation in presence of noncondensable gas under natural convection. The effects of N_2 and Ar on the steam condensation were investigated, the pressure ranged from 0.516 to 5.10 MPa, and the mass fraction of nitrogen/argon varied from 5% to 85%. According to the experimental results, some conclusions were obtained as follows:

(1) The spatial distributions of N_2 and Ar in the steam/gas mixture were relatively uniform and there was no obvious stratification phenomenon. When the primary pressure varied from 0.517 to 5.10 MPa and the gas temperature varied from 110°C to 249°C, the differences in the mass fraction of nitrogen/argon in the axial direction were less than 2.7% and had similar trends when the axial distance increased.

(2) When the pressure was 0.52 MPa and the mass fraction of nitrogen was 47%, the total heat transfer coefficient of steam condensing on the wall was 0.215 kW/(m^2·K) and the heat transfer coefficient remained basically unchanged with the increase of the total heat transfer temperature difference. The heat transfer coefficient of steam condensation decreased with the increase of the degree of supercooling of the wall. The difference of steam condensation heat transfer coefficient was approximately 0.11 kW/(m^2·K) when the degree of supercooling increased from 14°C to 36°C. Therefore, the influences of total heat transfer temperature difference on the steam condensation could be ignored, while the degree of supercooling of the wall should be controlled in a very small range as far as possible during the experiments.

(3) The concentration of noncondensable gas was a vital factor affecting the heat and mass transfer in steam condensation. When the pressure was 0.517 MPa and the mass fraction of nitrogen varied from 9.03% to 75.76%, the condensation heat transfer coefficient decreased from 1.393 to 0.165 kW/(m^2·K). For the other pressure conditions and argon, the steam condensation heat transfer coefficients showed the same law of change. And it is obvious that the effects of the molar fraction of the noncondensable gas were consistent with the effects of the mass fraction of the noncondensable gas on the steam condensation heat transfer coefficient on the vertical wall.

(4) The pressure also played a key role in the heat transfer of steam condensation with noncondensable gas. The pressure was able to greatly enhance the steam condensation heat transfer; for example, the heat transfer coefficient with N_2 varied from 0.757 to 4.26 kW/(m^2·K) for the pressure from 0.214 MPa to 5.12 MPa. However, the characteristics of enhancement of pressure on steam condensation heat transfer were a little different for N_2 and Ar.

Data Availability

The data are not available due to the trade secret.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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