Research Article

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Experimental investigation on steam/nitrogen condensation characteristics inside horizontal enhanced condensation channels

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Abstract: In order to investigate heat transfer characteristics of steam/nitrogen condensation inside horizontal enhanced condensation channels (HECCs), experiments have been performed, respectively, inside HECC and horizontal circular channel (HCC). HECC is formed by inserting different reinforcers into HCC including horizontal multi-start straight channels (HMSSCs) and horizontal spiral channels (HSCs). Effects of nitrogen mass fractions on average condensation heat transfer coefficients (CHTCs), average outlet condensate mass flowrates (CMFRs), and average steam-side pressure drops (SSPDs) are analyzed, respectively. The results indicate that HECC has better condensation performance than HCC under the same conditions, while average SSPDs of HECC will increase slightly. Then, HMSSC is compared against HCC, and enhancement factors of average CHTCs and average outlet CMFRs are about 1.45 and 1.12, respectively, while the enlargement factor of average SSPDs is about 1.16. Similarly, HSC is compared against HCC, and enhancement factors of average CHTCs and average outlet CMFRs are about 1.25 and 1.05, respectively, while the enlargement factor of average SSPDs is about 1.12.

Keywords: steam/nitrogen condensation, horizontal enhanced condensation channels, criterion correlation, heat transfer enhancement mechanism

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Nomenclature

A	area, m^2
c_p	specific heat capacity at constant pressure, $\text{J kg}^{-1} \text{K}^{-1}$
d	diameter, m
d_e	equivalent diameter, m
G	mass velocity, $\text{kg m}^{-2} \text{s}^{-1}$
h_i	condensation heat transfer coefficient, $\text{W m}^{-2} \text{K}^{-1}$
h_o	convection heat transfer coefficient, $\text{W m}^{-2} \text{K}^{-1}$
H	enthalpy, kJ kg^{-1}
J_v	dimensionless vapor mass velocity
k	overall heat transfer coefficient, $\text{W m}^{-2} \text{K}^{-1}$
L	effective length, m
$\dot{m}$	mass flowrate, kg h^{-1}
Nu	Nusselt number
Pr	Prandtl number
q	heat flux density, W/m^2
Re	Reynolds number
t	temperature, $^{\circ}\text{C}$
Δt_m	log mean temperature difference, $^{\circ}\text{C}$
x	steam quality
X_{tt}	Martinelli parameter

Greek symbols

λ	thermal conductivity, $\text{W m}^{-1} \text{K}^{-1}$
μ	dynamic viscosity, Pa s
ν	kinematics viscosity, $\text{m}^2 \text{s}^{-1}$
ρ	density, kg m^{-3}
Φ	heat flowrate, W
ω	nitrogen mass fraction

Subscripts

c	condensation
cw	cooling water

i	inner, interface
in	inlet
l	liquid
m	mixture
n	nitrogen
o	outer
oc	outlet condensate
o $\bar{s}$	outlet uncondensed steam
out	outlet
s	steam
si	inlet steam
w	tube wall
wi	inner tube wall
wo	outer tube wall

Superscripts

'	inlet
"	outlet
+	heat absorption
–	heat release

Abbreviations

CHTC	condensation heat transfer coefficient
CMFR	condensate mass flowrate
ETB	experimental test body
HCC	horizontal circular channel
HECC	horizontal enhanced condensation channel
HMSSC	horizontal multi-start straight channel
HSC	horizontal spiral channel
NC	noncondensable
SSPD	steam-side pressure drop

1 Introduction

Heat transfer performance widely exists in the natural environment and industrial production, and the heat transfer enhancement research is carrying on continuously [1,2]. Because of compact structure, constant temperature control, and high heat transfer efficiency, condensers are widely used in energy, power, aerospace, and other industrial fields. In practice, steam condensation involves a complex phase-change heat transfer process and is affected by many factors, especially when the steam condensation is carried out inside the horizontal

restricted channels with a small amount of noncondensable (NC) gas. Therefore, it is extremely necessary for us to continuously study the steam condensation mechanism and heat transfer characteristics with NC gas inside the horizontal restricted channels.

As everyone knows, steam condensation will occur and be maintained as long as its dew-point temperature is above the surface temperature of the horizontal condenser tube. In the steam condensation process, the latent energy of the steam is released, and then the non-uniform condensate liquid film is formed. The steam molecular flux from and to the liquid–steam interface is controlled. Condensation conducts when the arrival rate of steam exceeds the departure rate, evaporation occurs during the opposite, and the two rates are equal during the equilibrium state [3]. However, when the steam contains NC gas, the condensation mechanism is very complicated. NC gas diffusion layer reduces the interface steam saturation temperature, that is, the driving force of steam condensation is reduced correspondingly. And in pure steam condensation, the condensate liquid film becomes the main thermal resistance of steam condensation. In steam and NC gas condensation processes, the NC gas diffusion layer (its thermal resistance is much higher than that of the condensate liquid film) comes to be the main resistance of steam/NC gas condensation. Moreover, the distribution of two-phase in the horizontal condenser tube is not as well understood as that in the vertical condenser tube [4,5]. The complexity mainly comes from two aspects: one is the nonsymmetrical gas–liquid two-phase distribution in the tube cross-section; the other is the symmetrical gas–liquid two-phase distribution in the vertical downflow condenser tube. When the steam/nitrogen velocity is low, the asymmetrical gas–liquid two-phase distribution caused by the density difference could affect the heat transfer [6], and the condensation heat transfer coefficients (CHTCs) at the top and bottom of the tube will be quite different.

In view of the complexity of steam and NC gas condensation in the horizontal condenser tube described above, much work has been performed experimentally [7–11] and theoretically [12–15]. In this respect, Sideman *et al.* [16] investigated experimentally the effect of air mass fractions on steam condensation performance inside the horizontal tube. The results showed that, when air mass fraction at the steam inlet is 3%, the average CHTC could decrease by 65% for the horizontal tube compared with pure steam. Ueno *et al.* [17] described the thermal hydraulics tests of steam condensation in the horizontal condensation tube and proposed empirical criterion correlations for the CHTCs. Nakamura [18] experimentally

investigated condensation of steam containing NC gas inside the horizontal u-shaped condenser tube and obtained the average CHTCs under specific conditions. It was found that mass fractions of NC gas had little effect on the condensation of steam inside the horizontal u-shaped condenser tube, proposing that horizontal u-shaped condenser tube has great potential in the PCCS system. Othmer [10] experimentally investigated steam-air condensation process inside the horizontal channel. The experimental results displayed that the average CHTC compared with pure steam would be decreased by 50% as air mass fraction was 0.5%. Wu et al. [5] experimentally studied the asymmetrical heat transfer performances of the steam and NC gas condensation inside a horizontal condenser tube. It was found that the differences of the CHTCs between the top and the bottom were not very significant at the outlet of the condenser tube, while near the inlet, the CHTCs at the top of the condenser tube were much higher than those at the bottom.

Caruso et al. [19,20] experimentally investigated steam/air condensation performance inside the horizontal tubes and inclined tubes, respectively, under a wide range of air mass fractions and atmospheric pressures, and the influences of tube diameter, air mass fraction, and inlet steam flowrate were analyzed. Besides, the correlations for steam/air condensation were proposed and the prediction Nu_{cal} were in good agreement with the experimental Nu_{exp} . Bespalov et al. [21] performed steam/air condensation experiments inside the horizontal rectangular channels with low inlet velocities ranging from 1.8 to 3.7 m/s, and they found that the CHTCs are related to the initial steam mass fractions and steam/air mass flowrates. Lee and Kim [22] utilized heat and mass transfer analogy to propose a theoretical model of pure steam condensation inside the horizontal tubes. The calculated CHTCs of this theoretical model slightly underestimated the experimental data at the top of the tube and slightly overestimated that at the bottom of it. Then, Lee and Kim [23] presented a new correlation for predicting the CHTCs of steam/NC condensation inside a horizontal tube. The predicted Nu_{cal} of the new correlation was good with the calculated Nu_{exp} of the existing theoretical model in Caruso et al. [24]. Cheng et al. [25] investigated experimentally the heat transfer performances of steam with NC gas condensation inside the horizontal rectangular channel. The influences of mixture mass fluxes, NC gas mass fractions, and coolant mass fluxes on the total CHTC were analyzed. The results show that the total CHTC would decrease 26.4% with 8% NC gas mass fraction. It indicated that when mixture mass fluxes were at higher speeds, the effect of NC gas

on steam condensation is not very obvious. Ahn et al. [26] developed a new condensation model for the nearly horizontal condenser tube. The condensation model was composed of a film condensation model and a convective model without phase transition. Ren et al. [4] studied experimentally the influence of NC gas mass fractions on the CHTCs inside the horizontal tubes and developed the correlations for steam/air condensation in the annular flow and the stratified flow, respectively. The results show that the local CHTCs at the bottom were lower than those at the top part owing to the asymmetrical gas–liquid film. The deviation between the predicted Nu_{cal} of the correlation and the calculated Nu_{exp} of the experimental data was within 20%.

In a word, although many researchers have experimentally and theoretically investigated the steam condensation inside the horizontal restricted channels and also obtained some significant achievements, there are very few studies on the steam/nitrogen condensation mechanisms inside the horizontal restricted channels, and there is no literature on steam/nitrogen condensation in HECCs.

In this article, steam/nitrogen condensation experiments were performed, respectively, inside the HECC and the horizontal circular channel (HCC) under the following conditions: steam pressure of 0.7 MPa, steam mass flowrate of 65 kg/h, nitrogen mass fractions of 0–10%, and cooling water mass flowrates of 2,500–4,000 kg/h. Inside the HCC, the influences of the nitrogen mass fractions on the average CHTCs in the condenser tube, the average condensate mass flowrates (CMFRs) at the outlet of the condenser tube, and the average steam-side pressure drops (SSPDs) between the inlet and the outlet of experimental test body (ETB) have been investigated, respectively. Moreover, a new fitting correlation for the average CHTCs of steam/nitrogen condensation in the HCC has been proposed. Finally, the average CHTCs, the average outlet CMFRs, and the average SSPDs of the HECC are compared with those of the HCC under the same conditions.

2 Experimental setup and test procedure

The experimental setup shown in Figure 1 was used for testing the heat transfer performance of steam/nitrogen condensation, which consists of the cooling water loop, steam loop, NC gas loop, ETB, measurement system, and

Figure 1: Experimental setup of steam/nitrogen condensation: (1) electronic boiler, (2) high pressure nitrogen cylinder, (3) pre-heater, (4) mixer, (5) ETB, (6) first separator, (7) condenser, (8) second separator, (9) floating ball steam trap, (10) water tank, (11) pump, (12) floating ball steam trap, (13) water tank, (14) pump, (15) water cooler, (16) water softener, and (17) data acquisition. Main legend: G: mass flowmeter; T: temperature; P: pressure.

data acquisition system. The cooling water softened by water softener (FLECK, USA) was stored in the tank for subsequent experimental use. The saturated steam was provided by an automatic electric heating steam boiler, and the steam pressure is 0.7 MPa and the steam temperature is 170°C under the rated condition. The NC gas (nitrogen) was provided by several high pressure nitrogen cylinders in series. The inlet pressure or mass flowrates were adjusted by the decompression valve. The NC gas was preheated by the preheater and finally mixed with the saturated steam in the mixer.

The ETB of HCC was composed of two concentric stainless steel tubes. The inner tube was a condenser tube, and the steam/nitrogen mixture flowed inside the condenser tube. The inner tube and the outer tube formed an annular interlayer, and the cooling water flowed countercurrently inside the annular interlayer. In the ETB, because the cooling water temperature was lower than the steam dew-point temperature, the steam was condensed continuously and the condensate was formed unceasingly.

The gas–liquid mixture from the outlet of ETB then flowed into the first gas–liquid separator, from which the

condensate steam, uncondensed steam, and nitrogen mixture were separated, respectively. Next, the uncondensed steam and nitrogen mixture flowed into an auxiliary condenser to make the remaining steam condensed completely. Then, the remaining condensate and nitrogen mixture entered the second gas–liquid separator to separate the condensate from the nitrogen again. Finally, two parts of condensate, respectively, flowed through floating ball steam trap and flowed into the condensate tank, and the final nitrogen was released into the atmosphere.

On the other hand, the cooling water from the water tank was pumped by a centrifugal pump into the ETB and absorbed the heat released by steam, and then flowed into a water–water cooler to release the absorbed heat in order to keep the water temperature in water tank constant. Besides, in order to avoid the stagnation zone and obtain uniform water flow distribution, the cooling water flowing into the ETB was evenly divided into two parts, and the cooling water flowing out of the ETB was discharged in the same way.

Finally, the collected condensate was pumped into the electronic boiler for the cycle operation. Forty-five T-type thermocouples with an accuracy of 0.1°C, seven

Figure 2: Sketch map of thermocouple positions.

Rosemount pressure transducers with an accuracy of $\pm 0.065\%$, and six calibrated mass flowmeters with an accuracy of $\pm 0.02\%$ were installed in the loop to measure their respective temperatures, pressures, and mass flow-rates, respectively.

Sketch map of thermocouple positions is shown in Figure 2. To measure the local outer wall temperatures of the condenser tube, at seven different axial locations as shown in Figure 2, 21 T-type thermocouple wires with a diameter of 0.2 mm were spot-welded onto the outer surface of the condenser tube. At the same axial locations, 19 T-type sheathed thermocouples with a diameter of 2 mm were installed at the midpoint of the annular interlayer through the cooling jacket wall to measure the local cooling water temperature in the annulus jacket. The ETB of horizontal spiral channel (HSC) was formed by inserting a twisted tape into the condenser tube of the aforementioned HCC. As shown in Figure 3, the stainless steel twisted tape with an outer diameter of 48.5 mm and an effective condensation length of 1.0 m was processed by lathe. The ETB of horizontal multi-start straight channels (HMSSC) was formed by inserting a multi-start straight-grooved rod into the condenser tube of the aforementioned HCC. As shown in Figure 4, the multi-start straight groove was machined by a milling machine along the axial direction on the surface of the smooth round rod. In addition to the twisted-tape and the multi-start straight-grooved rod, three sects of ETB had the same structure and size. Both the ETB of HSC and the ETB of HMSSC are designated as the ETB of HECC. Table 1 displays the summary of main parameters of the ETBs. Figure 5 shows the picture of the ETBs.

KEITHLEY-2700 data acquisition unit with a maximum data sampling rate of 100 kHz was used to record the measured values of the temperatures, the pressures or

Figure 3: Physical picture of twisted-tape.

Figure 4: Physical picture of multi-start straight-grooved rod.

Table 1: Summary of main parameters of the ETB

Configuration and parameter	Value
Experimental condenser tube	
Tube effectively length (mm)	1,000
Inner tube ID (mm)	50
Tube thickness (mm)	3
Jacket ID (mm)	80
Tube material	304 stainless steel
Jacket material	304 stainless steel
Multi-start straight-grooved rod	
Effectively length (mm)	1,000
Fin width (mm)	5
Groove depth (mm)	8.75
Groove numbers	6
Rod OD (mm)	48.5
Grooved rod material	304 stainless steel
Twisted tape	
Effectively length (mm)	1,000
Tape width (mm)	49.5
Tape thickness (mm)	2
Tape pitch (mm)	650
Twist ratio	0.076
Twisted tape material	304 stainless steel

Figure 5: Physical picture of the ETS.

pressure losses, mass flowrates, and then the collected data were input into the computer.

3 Theoretical calculation and uncertainty analysis

The inlet nitrogen mass fraction is calculated by the following equation:

$$\omega = \dot{m}_n / \dot{m}_m. \quad (1)$$

The heat absorbed by the cooling water in the ETB is obtained by the following equation:

$$\Phi^+ = \dot{m}_w c_p (t''_{cw} - t'_{cw}). \quad (2)$$

The heat released by the steam condensation in the ETB is obtained by equation (3):

$$\Phi^- = \dot{m}_{si} H_{si} + \dot{m}_{ni} H_{ni} - \dot{m}_{oc} H_{oc} - \dot{m}_{os} H_{os} - \dot{m}_{no} H_{no}. \quad (3)$$

The average heat flowrate in the ETB is defined as:

$$\Phi = (\Phi^+ + \Phi^-) / 2. \quad (4)$$

The heat fluxes of inner and outer surfaces of the condenser tube in the ETB are calculated by the following equations:

$$q_i = \Phi / \pi d_i L, \quad (5)$$

$$q_o = \Phi / \pi d_o L. \quad (6)$$

On the cooling water side in the ETB, the convective heat transfer coefficient can be obtained:

$$h_o = q_o / (\bar{T}_{wo} - \bar{T}_{cw}). \quad (7)$$

The logarithmic mean temperature difference Δt_m in the ETB is defined as:

$$\Delta t_m = \frac{\Delta t_{\max} - \Delta t_{\min}}{\ln \left(\frac{\Delta t_{\max}}{\Delta t_{\min}} \right)}. \quad (8)$$

According to the law of heat transfer, the overall heat transfer coefficient k of the ETB

$$k = q_o / \Delta t_m. \quad (9)$$

The overall heat transfer coefficient k of the ETB (regardless of fouling resistance)

$$\frac{1}{k} = \frac{1}{h_o} + \frac{d_o}{2\lambda} \ln \frac{d_o}{d_i} + \frac{d_o}{h_i d_i}. \quad (10)$$

Finally, the CHTC h_i of steam side in the ETB could be obtained by solving equation (10).

According to the uncertainty estimation method and uncertainty propagation equation proposed by Kline and McClintock [27], the uncertainties of the tube diameter and the tube length are $\pm 0.19\%$ and $\pm 0.08\%$, respectively, the uncertainties of the temperatures, pressures, and mass flowrates are, respectively, $\pm 0.45\%$, $\pm 0.15\%$, and $\pm 4.86\%$, and the uncertainties for the heat flowrates and the CHTCs are approximately $\pm 6.49\%$ and $\pm 9.56\%$.

4 Experimental results and discussion

In order to study the heat transfer characteristics in the HECC, the experiments of steam/nitrogen condensation in the HECC and in the HCC were performed and compared under the same experimental conditions.

4.1 System validation

Only when the thermal equilibriums are within $\pm 10\%$, the experimental system is considered to achieve the steady conditions, and then the data are collected. As depicted in Figure 6, the relative heat balance rate between the steam/nitrogen side and the cooling water side in the ETB is within 10% for more than 99% of all data. The deviations between the calculative Nu_{cal} from several correlations [28] for the cooling water side and the experimental Nu_{exp} obtained in the article are less than 10%, as shown in Figure 7. This indicates that the experiment data are reasonable and reliable.

Figure 6: Deviations of thermal equilibrium.

Figure 8: Nitrogen mass fraction effect on average CHTCs in HCC under different water flowrate conditions.

Figure 7: Deviations of experimental Nu_{exp} and calculative Nu_{cal} .

4.2 Characteristics of the HCC

First, under conditions of 0.7 MPa steam pressure, 65 kg/h steam mass flowrates, 0–10% nitrogen mass fractions, and 2,500–4,000 kg/h cooling water mass flowrates, steam/nitrogen condensation experiments inside the HCC have been conducted.

The effect of nitrogen mass fraction on the average CHTCs inside the HCC under different cooling water flowrate conditions is displayed in Figure 8. It is found that the average CHTC of steam condensation inside the HCC decreases remarkably with the increase in inlet nitrogen mass fraction. Compared with pure steam, the average CHTC integrally decreases by 22% with 2% nitrogen mass fraction, and the average CHTCs decrease 30%

and 45%, respectively, with 5% and 7% nitrogen mass fractions. When the nitrogen mass fraction reaches 10%, the average CHTCs decrease by 58% ultimately.

When steam/nitrogen condensation occurs in the condenser tube of the ETB, the liquid film of the condensate is formed symmetrically and unevenly on the inner wall of the horizontal condenser tube. Nitrogen cannot pass through the liquid film of the condensate, and then accumulates between the steam and the condensate to form a nitrogen diffusion layer. The thickness increases gradually along the direction of steam flow. Moreover, with the increase in the nitrogen mass fraction, the nitrogen boundary layer becomes more and more thick. In addition, steam can be condensed when it passes through the nitrogen diffusion layer by means of convection or diffusion. As a result, the nitrogen boundary layer becomes the main factor to restrict the further condensation of steam, and the average CHTCs of the ETB will decrease significantly compared with pure steam.

The effect of nitrogen mass fraction on the average outlet CMFR inside the HCC under different cooling water flowrate conditions is exhibited in Figure 9. It is obvious that the average outlet CMFR of the ETB decreases correspondingly with the increase in the nitrogen mass fractions, similar to the average CHTC of the ETB. As shown in Figure 9, the average outlet CMFR of the ETB decreases integrally by 8% with 2% inlet nitrogen mass fraction. When the nitrogen mass fraction is 5% and 7%, respectively, the average outlet CMFRs of the ETB decrease by 11% and 14% accordingly. If the nitrogen mass fraction increases to 10%, the average outlet CMFR of the ETB decreases by 15% ultimately. However, with the increase in the inlet cooling water mass flowrate, both the average

Figure 9: Nitrogen mass fraction effect on outlet CMFRs in HCC under different water flowrate conditions.

CHTC and the average outlet CMFR increase in varying degrees.

4.3 Experimental correlation

The experimental data are compared with the existing criterion correlation. Caruso's criterion correlation [18] (equation (11)) was used to compare with the experimental data in the HCC:

$$Nu_s = 18.8 Re_m^{0.592} Re_l^{-0.13} \left(\frac{\omega}{1-\omega} \right)^{-0.357}. \quad (11)$$

Figure 10 shows the contrast of experimental Nu_{exp} and calculative Nu_{cal} inside the HCC. From Figure 10, it is found that the experimental Nu_{exp} calculated directly with the experimental data are not consistent with the Nu_{cal} calculated by Caruso's correlation. The main reason is that Caruso's correlation is fitted based on the data of steam/air condensation in the horizontal tubes with an inclination angle of 7° . Therefore, it is very necessary to establish a new correlation for steam/nitrogen condensation inside the HCC.

Based on the experimental data of steam/nitrogen condensation inside the HCC, a new fitting correlation is proposed as follows:

$$Nu_s = 3.05 Re_m^{0.724} Re_l^{-0.08} \left(\frac{\omega}{1-\omega} \right)^{-0.229}, \quad (12)$$

where the inlet steam Nu_s , inlet steam/nitrogen mixture Re_m , and outlet condensate Re_l , respectively, are as follows:

Figure 10: Contrast of experimental Nu_{exp} and calculative Nu_{cal} of Caruso's correlation in HCC.

$$Nu_s = \frac{h_i d_i}{\lambda_s}, \quad (13)$$

$$Re_m = \frac{4\dot{m}_m}{\pi \mu_m d_i}, \quad (14)$$

$$Re_l = \frac{4\dot{m}_l}{\pi \mu_l d_i}. \quad (15)$$

Experimental range of the correlation (equation (12)): a steam pressure of 0.7 MPa, an inlet steam mass flowrate of 65 kg/h, inlet nitrogen mass fractions 0–10%, a dimensionless steam mass velocity $J_v < 0.9$, and a Martinelli parameter $X_{tt} < 1$.

$$J_v = \frac{xG_{m,i}}{[\rho_l(\rho_l - \rho_n)d_i]^{0.5}}, \quad (16)$$

Figure 11: Contrast of experimental Nu_{exp} and predicted Nu_{cal} of fitting correlation proposed in the article in HCC.

$$X_{tt} = \left(\frac{1-x}{x} \right)^{0.9} \left(\frac{\mu_1}{\mu_s} \right)^{0.1} \left(\frac{\rho_s}{\rho_l} \right)^{0.5}. \quad (17)$$

The contrast between the calculative Nu_{cal} calculated by equation (12) and the experimental Nu_{exp} calculated directly with experiments data is shown in Figure 11. The results show that the calculative Nu_{cal} are consistent with the experimental Nu_{exp} for steam/nitrogen condensation inside the HCC, and all of the data points are within the range of $\pm 15\%$ error, with the correlation coefficient of 0.903 and a standard error of 0.175, respectively.

4.4 Contrast of characteristics between HECC and HCC

Subsequently, steam/nitrogen condensation experiments inside the HECC were mainly investigated emphatically under the same conditions (see Section 4.2 for details). Finally, under the same conditions, the average CHTC, the average outlet CMFR, and the average SSPD of the HECC were compared separately with those of the HCC. Steam/nitrogen condensation characteristics are summarized in Table 2.

The comparison between the average CHTC for the HECC and the HCC is demonstrated in Figure 12. Since the HECC consists of the HMSSC and the HSC, the discussion will elaborate separately. As seen in Table 2, under the same conditions, the average CHTC of the HMSSC is approximately 1.45 times as much as that of the HCC, and it could be defined that the enhancement factor of the average CHTC in the HMSSC is 1.45. In a similar way, under the same conditions, the average CHTC of the HSC

is approximately 1.25 times as much as that of the HCC, the enhancement factor of the average CHTC in the HSC is 1.25. It is obvious that, under the same conditions, the average CHTC of the HECC is significantly better than that of the HCC.

The comparison between the average outlet CMFR for the HECC and the HCC under the same conditions is displayed in Figure 13. Similarly, we will also elaborate separately them as follows. As shown in Table 2, the average outlet CMFR of the HMSSC is approximately 1.12 times as much as that of the HCC. Similarly, we can get that the average outlet CMFR of the HSC is approximately 1.05 times as much as that of the HCC. It is clear that, under the same conditions, the average outlet CMFRs of the HECC are also slightly more than those of the HCC, similar to the average CHTCs of the HECC.

The reinforcement mechanism of the HECC is as follows: when the multi-start straight channel rod and the twisted-tape are inserted, respectively, into the condenser tube, the increase in the gas–liquid mixture velocity would lead to a thinner condensate thickness in varying degrees, and the changes of the gas–liquid flow direction would strengthen the disturbance of the steam–nitrogen diffusion layer. The strong disturbance would further lead to the destruction of the continuous diffusion layer of the nitrogen, which would lead to the further condensation of the steam ultimately. There are some unfavorable factors, such as the decrease in gas–liquid effective circulation area and the increase in average in-tube steam velocity, but the enhancement of gas–liquid disturbance, especially the destruction of the continuous diffusion layer of the nitrogen, is the most important factor affecting steam condensation. Therefore,

Table 2: Summary of steam/nitrogen condensation characteristics

	HCC	HMSSC	HSC
Type	Film condensation	Film condensation	Film condensation
Steam-side channels of ETB	HCC	HMSSC	HSC
Water-side channel of ETB	Annulus jacket	Annulus jacket	Annulus jacket
Water-side equivalent diameter (mm)	23	23	23
Cooling water mass flowrates (kg/h)	2,500–4,000	2,500/4,000	2,500/4,000
NC gas	Nitrogen	Nitrogen	Nitrogen
Steam pressure (Pa)	0.7	0.7	0.7
Inlet steam mass flowrates (kg/h)	65	65	65
Steam-side equivalent diameter (mm)	50	10	50
Inlet nitrogen mass fractions (%)	0, 2, 5, 7, 10	0, 2, 5, 7, 10	0, 2, 5, 7, 10
CHTCs (W/m ² K)	2.157–5.294	3.055–7.107	2.462–6.280
CMFRs (kg/h)	24.887–32.933	26.711–39.815	25.407–36.375
Enhancement factor of CHTCs	1	1.45	1.25
Enlargement factor of CMFRs	1	1.12	1.05
Enlargement factor of SSPDs	1	1.16	1.12

Figure 12: Comparison between the average CHTCs of the HECC and those of the HCC under the same conditions.

the experimental results show that the destruction of the nitrogen diffusion layer and the thinner condensate thickness greatly promote steam condensation eventually.

Under the same conditions, the comparison between the average SSPDs of the HECC and those of the HCC is evinced in Figure 14. Generally speaking, the average SSPDs between inlet and outlet in the ETB will reduce slightly with the increase in the nitrogen mass fraction, while the average SSPD will increase gently with the increase in the cooling water mass flowrate. The comparison results indicate that, under the same conditions, the average SSPD of the HMSSC is approximately 1.16 times as much as that of the HCC (similarly, define the enlargement factor of the average SSPD in the HMSSC as 1.5), and

Figure 14: Comparison between the average SSPDs of the HECC and those of the HCC under the same conditions.

that the average SSPD of the HSC is approximately 1.12 times as much as that of the HCC (in a similar way, define the enlargement factor of the average SSPD in the HSC as 1.5). The comparison results are summarized in Table 2. The reason for the surge of the average SSPDs in the HECC is that more steam is condensed. The conclusion is that the HECC can effectively enhance the heat transfer of steam condensation, but the average SSPDs in the HECC will increase correspondingly.

When the multi-start straight channel rod and the twisted-tape are inserted, respectively, into the condenser tube, larger friction loss and more steam condensed are the main reasons for the enlargement of the average SSPDs between inlet and outlet in the ETB. The conclusion is that the HECC can effectively improve the average CHTCs and the average outlet CMFRs, but the average SSPDs in the HECC will increase correspondingly.

Figure 13: Comparison between the average outlet CMFRs of the HECC and those of the HCC under the same conditions.

5 Experimental conclusions

The experimental investigation aimed to ascertain the heat transfer performance of steam/nitrogen condensation in the HECC. The main conclusions are drawn.

- (1) A new fitting correlation for steam/nitrogen condensation in the HCC is proposed. The results indicate that the predicted Nu_{cal} of the correlation is in good agreement with the experimental Nu_{exp} , and the deviation between the predicted Nu_{cal} and the experimental Nu_{exp} is less than $\pm 15\%$. The mass fraction of nitrogen has a significant effect on the condensation characteristics of steam.

- (2) All results reveal that the mass fraction of nitrogen has a significant impact on the heat transfer performances of steam condensation both in the HECC and in the HCC. The average CHTC, the average outlet CMFR, and the average SSPD will decrease at varying level with the increase in nitrogen mass fraction. However, the average CHTC, the average outlet CMFR, and the average SSPD will increase in varying degree with the increase in the cooling water mass flowrate.
- (3) The comparison results indicate that, under the same experimental conditions, HECC has better heat transfer performance than HCC. Under the same experimental conditions, the average CHTC, the average outlet CMFR, and the average SSPD inside the HECC are approximately 1.45, 1.12, and 1.16 times as much as that of the HCC, respectively. The average CHTC, the average outlet CMFR, and the average SSPD inside the HSC are approximately 1.25, 1.05, and 1.12 times as much as those of the HCC, respectively. It is clear that the HECC can effectively improve the heat transfer performance of steam/nitrogen condensation, but the average SSPD between inlet and outlet in the HECC will increase correspondingly.

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