Research Article

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Experimental study on enhancement characteristics of steam/nitrogen condensation inside horizontal multi-start helical channels

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Abstract: The aim of this study was to reveal the internal mechanism of enhanced condensation heat transfer, by experimentally performing steam condensation with higher inlet velocity in the horizontal multi-start helical channels (HMSHCs), and investigating the influences of pressure of steam, mass flowrate of cooling water, and mass fraction of noncondensable (NC) gas on steam condensation performance. Taking steam condensation in horizontal circular condensation channel (HCCC) as a reference, the condensation heat transfer coefficients (CHTCs), the outlet condensate mass flowrates (CMFRs), and the total steam condensation pressure drops (SCPDs) were compared and discussed, respectively. The results indicated that NC gas had a strong inhibitory effect on steam condensation, and average condensation characteristics decreased with the increase in NC gas fraction for lower Re_m . But for higher Re_m , the gas–liquid interfacial shearing stress can likely weaken the negative effect of NC gas. In addition, increasing the cooling water flowrate can entirely promote steam condensation. The comparison results indicated that steam condensation

performance of HMSHC is better than that of HCCC under same experimental conditions. For the specific experimental scope, the average CHTCs and the outlet CMFRs in HMSHC are approximately 2.35 and 1.25 times of that inside HCCC, respectively, while the overall SCPDs in HMSHC are about 1.16 times of that inside HCCC. After introducing the performance evaluation factor, the calculation results revealed that the performance evaluation factor h_{PEC} of the average CHTCs in HMSHC is approximately 2.02, and the performance evaluation factor m_{PEC} of the outlet CMFRs in HMSHC is approximately 1.08. The two evaluating values are reasonable.

Keywords: enhanced steam condensation, horizontal multi-start helical channels, correlations, performance evaluation factor

Nomenclature

c_p	specific heat capacity at constant pressure, $J\ kg^{-1}\ K^{-1}$
d	tube diameter, m
G	specific mass flux, $kg\ m^{-2}\ s^{-1}$
h	heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
H	enthalpy, $kJ\ kg^{-1}$
J_s	dimensionless steam velocity (Wallis parameter)
m	mass flowrate, $kg\ h^{-1}$
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
T	temperature, K
x	steam quality
X_{tt}	Martinelli number

Greek symbols

λ	thermal conductivity, $W\ m^{-1}\ K^{-1}$
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μ	dynamic viscosity, Pa s
ρ	density, kg m ⁻³
Φ	heat flowrate, W
ω	mass fraction of NC gas

Subscripts

c	condensate or condensation
e	Enhancement
i	inner, interface
l	liquid
m	mixture
n	nitrogen
o	outer
r	reference
s	steam
$\bar{s}$	uncondensed steam
w	wall

Superscripts

'	entrance
"	exit
+	absorption
-	release

Abbreviations

CHTC	condensation heat transfer coefficient
CMFR	condensate mass flowrate
ETS	experimental test section
HCCC	horizontal circular condensation channel
HMSHC	horizontal multi-start helical channel
NC	noncondensable
NCGMF	noncondensable gas mass fraction
SCPDs	steam condensation pressure drops

1 Introduction

Due to the strong heat transfer ability, constant temperature control, compact structure, and other advantages, steam condenser of the horizontal in-tube condensation type are widely used in many industrial fields. However,

in the horizontal restricted channels, there are numerous factors restraining steam condensation, making the condensation process extremely complicated due to the symmetrical and nonuniform distribution characteristics of the liquid film in the axial and circumferential directions. Especially when there is a small amount of noncondensable (NC) gas, the existence of NC gas will deteriorate seriously the heat transfer performance because of the NC gas diffusion layer [1,2]. Therefore, exploring the horizontal enhanced condensation channels to improve the steam condensation characteristics is of great significance for the optimal design of condensers.

The effect of the NC gas mass fractions (NCGMFs) on the steam condensation characteristics has been extensively studied both experimentally [3–15] and theoretically [16–21] in the horizontal restricted channels. In this respect, Othmer [5] was the first to carry out experimental research on the condensation of steam-air mixture on an isothermal condensing surface. It was surprisingly found that, when the air concentration is 0.5%, the average condensation heat transfer coefficient (CHTC) is 50% lower than that of pure steam, which arouse many scholars' interest in the research of steam condensation in the presence of NC gas. Sideman *et al.* [6] conducted an experimental investigation on the effects of tube cross-section shape and air mass fraction on steam condensation characteristics under different conditions. He found that the average CHTC of steam with 3% air is 65% lower than that of pure steam in the horizontal condenser tube, and the average CHTC in the horizontal elliptical tube is 20% higher than that in the horizontal circular tube, under the same conditions. Nakamura *et al.* [7] experimentally assessed the impact of NCGMFs on the average value of steam CHTCs in the horizontal single U-tube under the postulated severe accident conditions. They found that NCGMFs had an insignificant impact on the average CHTCs in the horizontal single U-tube even at high NCGMFs. Wu and Vierow [8] experimentally studied the effect of NCGMFs on the average CHTC of vapor condensation in the horizontal condenser tube, and investigated the asymmetrical heat transfer characteristics around the condenser tube periphery. They found that the CHTCs of the tube top and tube bottom surface near the entrance and near the outlet of the condenser tube were significantly different for lower mixture inlet Reynolds number.

Caruso *et al.* [9–11] experimentally investigated the steam condensation characteristics inside the condenser tubes with different inclination angles in a wide range of NCGMF. The effect of tube diameter (12.6, 20, and 26.8 mm), air mass fraction (2–42%), and tube inclination (0, 7, 15, 30, and 45°) on the average CHTCs of steam condensation were

analyzed. The criterion correlations to evaluate the local CHTCs of the steam/air mixtures condensation were proposed. They found that NC gas did reduce the steam condensation characteristics inside the condenser tubes with different inclination angles, and that the predicted Nu_{cal} was in good agreement with the experimental Nu_{exp} for gravity-controlled stratified flow. Ren *et al.* [12] experimentally investigated the steam condensation characteristics in the horizontal circular condensation channel (HCCC) in the presence of NC gas, and analyzed the effect of NCGMFs on the local CHTCs near the entrance and the outlet of the condensing tube. The correlations of the local CHTCs, respectively, for the stratified or annular flow regimes were developed, and the error was within $\pm 20\%$. They found that, near the entrance of the condenser tube, the local CHTCs at the bottom of the condenser tubes were smaller than that at the top of the tubes due to the asymmetrical liquid film thickness profile. While near the outlet of the condensing tube, the relative deviation gradually decreased along the axis direction of the condenser tube, especially at higher NCGMFs.

Cheng *et al.* [13] experimentally studied the steam condensation characteristics with higher inlet velocity in a small horizontal rectangular channel. It was found that the overall CHTCs could go down by 26.4% with an 8% inlet NCGMF, while NCGMF had no evident influence on steam condensation performance when inlet mixture mass flux was large. Xu *et al.* [14] experimentally investigated the steam condensation performances for annular, wavy, and stratified flow inside a horizontal tube containing multicomponent NC gases. They found that the local CHTCs increased with the increase in the condensation temperature difference for annular and wavy flow but decreased for stratified flow. Moreover, they also displayed that the calculated Nu_{cal} from the proposed correlation were in good agreement with the experimental Nu_{exp} with satisfactory engineering accuracy.

Shen *et al.* [15] performed an experimental investigation on steam condensation characteristics for the stratified flow regime in a horizontal vacuum tube. They found that the local CHTCs in film condensation section were evidently higher than that in the condensate gathering section, and the former decreased with the increase in the condensation temperature difference, while the latter had less effect on that. Furthermore, new correlations for predicting the local CHTCs of steam condensation in the horizontal vacuum tube under stratified flow pattern were proposed.

Due to the uneven circumferential distribution structure of liquid film inside the horizontal tube, most studies on the heat transfer characteristics of steam condensation

in horizontal tube used experimental methods. However, some scholars have simplified the flow and heat transfer process in the horizontal tube and obtained a series of simple models for calculating the CHTCs. Lee and Kim [19] developed a theoretical model to investigate steam condensation performances with NC gas inside a horizontal condenser tube. The method of heat and mass analogy was applied to analyze the steam/NC gas mixture boundary layer. It was found that, for stratified flow with higher mixture velocity, based on the measured data at the bottom of the horizontal condenser tube, the local CHTCs obtained from the theoretical model slightly overestimated those calculated by theoretical formula. While based on the experimental data at the top of the horizontal condenser tube, the local CHTCs obtained from the theoretical model slightly underestimated those calculated by theoretical formula. In addition, the predicted CHTCs of the empirical correlation proposed by Lee and Kim [20] were in good agreement with those of the theoretical model. Ahn *et al.* [21] proposed a steam condensation heat transfer model package to improve the prediction capability of the upper and lower parts of the nearly-horizontal tube under the air-water and steam-water separated flow conditions, when considering the effects of interfacial shear stress resulting from a high convective steam flow. The experimental results showed that the calculative h_{cal} of the model was in good agreement with the experimental h_{exp} with only an average deviation of 6.2%, which indicated that the prediction performance of the condensation model was significantly improved.

About strengthening the condensation heat transfer, other scholars have also proposed many technologies of enhanced condensation heat transfer in the horizontal channel. For example, some horizontal microfin tubes with external extended surface (such as 3-D finned tubes, spiral finned tubes, serrated finned tubes, slotted finned tubes, *etc.*) [22,23], some horizontal non-circular channels (such as triangular channels, elliptical channels, rectangular channels, *etc.*), microchannel, and enhanced heat exchanger with nanoparticles are used for heat transfer enhancement [24–29]. However, most of the working fluids in the literature are concentrated on water, refrigerants, nanofluids, and so on, and less on steam enhancement condensation in the horizontal channels.

Although many researchers have studied steam condensation characteristics in the horizontal confined channel through experiments, theories, and even simulations, most of them are low steam flow velocity or are mostly in horizontal smooth tubes, and very few works were performed to study steam condensation characteristics inside the horizontal enhanced condensation channels with NC

gas. Therefore, in this study, nitrogen was used as NC gas ($\omega_{i,n} = 0\text{--}10\%$), steam/nitrogen condensation experiments inside horizontal multi-start helical channel (HMSHC) would be performed and compared with that inside HCCC under same conditions.

2 Experimental system and procedure

The schematic diagram of steam condensation experiment is shown in Figure 1, which were composed of steam pipeline system, NC gas pipeline system, cooling water pipeline system, experimental test section (ETS), data acquisition system, and so on. Forty-five T-type thermocouples with the precision less than $\pm 0.1^{\circ}\text{C}$, seven Rosemount pressure transducers with the precision less than $\pm 0.065\%$, and six Coriolis mass flowmeter with the precision less than $\pm 0.02\%$ were installed on the pipeline to measure the temperature, pressure, and mass flowrate, respectively.

The cooling water softened by FLECK water softener was used as coolant, and stored separately in the cooling water tank and in the condensate tank to be used. The

steam required for the experiment was supplied by a steam generator, under the rated conditions, with corresponding pressure of 0.7 MPa, temperature of 170°C, and mass flowrate of 65 kg h⁻¹. Nitrogen was used as NC gas in the study, which was provided by high pressure gas cylinders, its pressure and mass flowrate were controlled by decompression valve, and its temperature was controlled by the preheater. Then, the steam (saturated pure steam) and the nitrogen (meeting the required state, with inlet NCGMF of 0–10%) were thoroughly mixed in the mixer. Here gas–liquid mixture (steam + nitrogen + condensate) in the condensing tube was used as thermal fluid.

The ETS of HCCC was a concentric-tube heat exchange consisting of two stainless steel tubes, and an annular interlayer was formed between the inner and outer tubes. The thermal fluid flowed inside the inner tube (the condenser tube), while the coolant flowed reversely in the annular interlayer. The ETS was well insulated, and the heat transfer between steam/nitrogen mixture and cooling water was mainly carried out through the condenser tube. In the ETS, due to condensation, the steam ceaselessly turned into the condensate to release heat, and NC gas (nitrogen) moved toward steam-condensate interface where they accumulate, and the temperature of the cooling water after absorbing heat raised correspondingly. The gas-liquid

Figure 1: Schematic diagram of steam condensation experiment.

mixture in the condenser tube flowed out of the ETS into the 1st gas–liquid separator. The condensate separated from the gas–liquid mixture flowed through ball float drain valve and flowed into the condensate tank. Then, the uncondensed steam and NC gas nitrogen mixture flowed into a water–gas cooler to make the uncondensed steam condense thoroughly. Finally, another condensate separated again by 2nd gas–liquid separator flows through ball float drain valve and also into the condensate tank. After being cooled down, the separated NC gas was discharged into the atmosphere through the check valve. The cooling water heated in ETS flowed into the next water cooler to be further cooled so as to make the inlet temperature of the cooling water constant in ETS. Steam generator absorbed the condensate in the condensate tank from time to time to maintain the continuous operation of the system.

The thermocouple layout is shown in Figure 2. Seven T type thermocouples on each row were arranged along the axial direction, and a total of 21 T type thermocouples in 3 rows with the diameter of 0.2 mm were welded on the outer surface of the condenser tube to measure the local temperatures of the outer surface, respectively. For the same reason, taking no account of two T type thermocouples at the cooling water inlet and outlet, a total of 19 T type armored thermocouples in 3 rows with the diameter of 2 mm passed through the outer tube to measure the local temperature of the cooling water in the annular interlayer, as shown in Figure 2. The picture of the thermocouple on the outer surface of the condenser tube is shown in Figure 3. The picture of the multi-start helical channel component is shown in Figure 4. The ETS of HMSHC was constituted only by infixing a multi-start helical channel component into the condenser tube of HCCC mentioned earlier. Now we think that the HMSHC is a horizontal enhanced condensation

Figure 3: Picture of the thermocouple on the condenser tube.

channel. Table 1 shows the comparison of the main structural parameters of ETSs. Figure 5 shows the picture of the ETS of HMSHC.

Finally, during the tests, the local temperature, pressure, and mass flowrate were all gathered by KEITHLEY-2700 data acquisition unit at interval of 5 s, and were saved in the computer for data processing. In each ETS, three important physical quantities of the average CHTCs, the outlet condensate mass flowrates (CMFRs), and the total steam condensation pressure drops (SCPDs) were separately obtained by using the conservation of mass and energy. Inside the HMSHC, performance evaluation factors of the average CHTCs and performance evaluation factors of the outlet CMFRs were introduced to evaluate the enhancement performance of steam condensation in the presence of NC gas nitrogen.

Figure 2: Sketch map of thermocouple layout.

Figure 4: Picture of multi-start helical channel component.

Table 1: Comparison of the main structural parameters of ETS

Configuration and parameters	Value
ETS of HCCC	
Effective length (mm)	1,000
Inner tube ID (mm)	50
Inner tube thickness (mm)	3
Outer tube ID (mm)	80
Inner tube material	304 stainless steel
Outer tube material	304 stainless steel
Multi-start helical channel component	
Effective length (mm)	1,000
Width of fin (mm)	5
Depth of slots (mm)	8.75
Numbers of slots	6
Slot distance (mm)	196
Component OD (mm)	48.5
Component material	High strength aluminum alloy

Figure 5: Picture of the ETS of HMSHC.

3 Experimental calculation and data processing

The inlet mass fraction of NC gas nitrogen is given by:

$$\omega_{i,n} = m_n/m_m, \quad (1)$$

where m is the mass flowrate and the subscripts n and m indicate the nitrogen and the mixture, respectively.

On the coolant side, the rate of heat absorption for the coolant in ETS is:

$$\Phi^+ = m_{cw}c_p(T''_{cw} - T'_{cw}), \quad (2)$$

where c_p is the specific heat, T is the temperature, the subscript cw indicates the cooling water, and the

superscript $'$ and $''$ indicate the entrance and the exit, respectively.

On the thermal fluid side, the rate of heat release from thermal fluid in ETS is:

$$\Phi^- = m_{is}H_{is} + m_{in}H_{in} - m_{oc}H_{oc} - m_{os}H_{os} - m_{on}H_{on}, \quad (3)$$

where H is the enthalpy, the subscripts is , in , oc , os , and on indicate the inlet steam, the inlet nitrogen, the outlet condensate, the outlet uncondensed steam, and the outlet nitrogen, respectively.

The average heat transfer rate Φ in ETS is:

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

By Newton's law of cooling, the convective heat transfer coefficient h_o on the outer surface of the condenser tube can be determined from

$$\Phi = \pi d_o h_o (\bar{T}_{ow} - \bar{T}_{cw}), \quad (5)$$

where $\bar{T}$ is the average temperature, the subscript ow indicates the outer wall of the condenser tube.

The ETS is a typical concentric-tube heat exchanger. If the fouling resistance is neglected, the average heat transfer rate Φ in ETS can also be determined from

$$\Phi = \frac{\bar{T}_{is} - \bar{T}_{cw}}{\frac{1}{\pi d_i h_i} + \frac{1}{2\pi\lambda} \ln \frac{d_o}{d_i} + \frac{1}{\pi d_o h_o}}, \quad (6)$$

where λ is the thermal conductivity of 304 stainless steel and d_i and d_o are the inner diameter and outer diameter of the condenser tube, respectively.

Finally, the condensation heat transfer coefficient h_i on the inner surface of the condenser tube could be obtained by solving equation (6).

Using the method in literature [30], the error propagation analysis had been performed to evaluate the uncertainty of the main physical quantity. It was found that the uncertainties of the heat transfer rates were approximately $\pm 7.00\%$, and the uncertainties of the average CHTCs were approximately $\pm 10.00\%$.

4 System validation

First, in the following experimental conditions: inlet steam partial pressure $P_{i,s} = 0.3\text{--}0.7$ MPa, inlet steam flowrates $m_{i,s} = 28\text{--}65$ kg h⁻¹, inlet NCGMFs $\omega_{i,n} = 0\text{--}10\%$, inlet cooling water flowrates $m_{i,cw} = 2,500\text{--}4,000$ kg h⁻¹, the relative heat balance rate, the cooling water flow characteristics, and the steam condensation characteristics inside HCCC were investigated and verified.

4.1 Validation of relative heat balance rate

Only tests with the differences in the heat balance within $\pm 10\%$ were considered. At this point, the whole steam condensation system was considered to reach a stable state, and the experimental data were recorded. As displayed in Figure 6, the heat balance rate between them were within 10% error for more than 99% of all data.

4.2 Validation of cooling water flow characteristics

On the coolant side, the cooling water convection characteristics were compared with the existing correlations [31]. The experimental Nu_{exp} obtained by the theoretical formula were compared with the predictive Nu_{cal} obtained by the correlations, validation is shown in Figure 7. The results showed that the deviations between the predictive Nu_{cal} and the experimental Nu_{exp} were less than 10%, indicating that the test data collected by data acquisition unit are reasonable and reliable.

4.3 Validation of steam condensation characteristics

On the thermal fluid side, the steam condensation characteristics were also compared with Caruso's correlation [11]. The experimental Nu_{exp} calculated by the theoretical formula were verified with the predictive Nu_{cal} from

Figure 6: Verification of heat balance rate.

Figure 7: Verification of experimental Nu_{exp} and predictive Nu_{cal} from the correlations.

Caruso's correlation, as shown in Figure 8. The results showed that the predictive Nu_{cal} were about 1.5–2.5 times of the experimental Nu_{exp} . The main reason for the deviation is due to different experimental conditions: Caruso's correlation was fixed with the test data inside the slightly inclined tube; however, the condenser tube in this study was horizontal with no inclination. Therefore, we need to establish a new criterion correlation according to the current situation.

Based on the test data, a new criterion correlation for the inlet steam Nu_s is proposed as follows:

$$Nu_s = 3.05 Re_m^{0.724} Re_l^{-0.08} \left(\frac{\omega}{1 - \omega} \right)^{-0.229}. \quad (7)$$

Figure 8: Verification of experimental Nu_{exp} and predictive Nu_{cal} of Caruso's correlation.

Experimental range: inlet NCGMFs is $0 \leq \omega \leq 10\%$, inlet steam/nitrogen mixture is $38,705 \leq Re_m \leq 40,025$, outlet condensate is $664 \leq Re_l \leq 766$, and gravity-controlled stratified region with dimensionless steam velocity is $J_s < 0.9$, and Martinelli number $X_{tt} < 1$. Descriptions of the stratified flow region controlled by gravity is given in ref. [32].

$$Nu_s = \frac{h_i d_i}{\lambda_s}, \quad (8)$$

$$Re_m = \frac{4\dot{m}_m}{\pi \mu_m d_i}, \quad (9)$$

$$Re_l = \frac{4\dot{m}_l}{\pi \mu_l d_i}, \quad (10)$$

$$J_s = \frac{x G_{m,i}}{[\rho_l(\rho_l - \rho_n) g d_i]^{0.5}}, \quad (11)$$

$$X_{tt} = \left(\frac{1-x}{x} \right)^{0.9} \left(\frac{\mu_s}{\mu_l} \right)^{-0.1} \left(\frac{\rho_s}{\rho_l} \right)^{0.5}. \quad (12)$$

The comparative verification between the experimental Nu_{exp} obtained by theoretical formula and the predictive Nu_{cal} obtained from equation (7) is shown in Figure 9. The results show that relative error between the experimental Nu_{exp} and the calculative Nu_{cal} are less than 10% for all data. The R^2 value is 0.905 and the Std Error is 0.176, Separately.

5 Experimental results and discussion

To reveal the internal mechanism of enhanced condensation heat transfer, taking steam condensation characteristics in the HCCC as a reference, steam condensation characteristics in HSMHC are experimentally investigated and discussed under the specific experimental conditions: inlet cooling water flowrates $m_{i,cw} = 2,500\text{--}4,000 \text{ kg h}^{-1}$, inlet steam partial pressure $P_{i,s} = 0.7 \text{ MPa}$, inlet steam flowrate $m_{i,s} = 65 \text{ kg h}^{-1}$, and inlet NCGMFs $\omega_{i,n} = 0\text{--}10\%$.

5.1 Characteristics of the HCCC

In view of the symmetrical and nonuniform characteristics of the liquid film in the horizontal condenser tube in the axial and circumferential directions, the average steam condensation characteristics inside the HCCC were first investigated. Influence of inlet NCGMFs on average

Figure 9: Verification of experimental Nu_{exp} and predictive Nu_{cal} of new fitting correlation.

CHTCs for different cooling water flowrates is shown in Figure 10. Figure 11 presents the influence of inlet NCGMFs on the outlet CMFRs for different cooling water flowrates. Figure 12 indicates the influence of inlet NCGMFs on the total SCPDs for different cooling water flowrates.

In Figures 10–12, taking the pure steam under rated condition as a reference, it can be concluded for a fixed steam flowrate and different inlet NCGMFs that when inlet nitrogen mass fraction is separately 2, 5, 7, and 10%, the average CHTCs decreases accordingly by 22, 30, 45, and 58%, severally, and the outlet CMFRs decreases correspondingly by 8, 11, 14, and 15%, respectively, and the overall SCPDs increase correspondingly by 7, 12, 17, and 20%, respectively. Moreover, in comparison to the pure steam, when the mass flowrate of the cooling water

Figure 10: Influence of inlet NCGMFs on average CHTCs for different cooling water flowrates.

Figure 11: Influence of inlet NCGMFs on outlet CMFRs for different cooling water flowrates.

Figure 12: Influence of inlet NCGMFs on overall SCPDs for different cooling water flowrates.

changes from 2,500 to 4,000 kg h⁻¹ with every 500 kg h⁻¹ increase, the average CHTCs approximately increase by 10%, and the outlet CMFRs increase correspondingly by 5%, and the overall SCPDs increase correspondingly by 6%. The results clearly indicated that all three physical quantities decreases in different degrees with the increment in inlet NCGMFs, and all the physical quantities increase with the increment in cooling water mass flowrates to varying degrees. The main reason of weakening steam condensation: the formation of nitrogen diffusion layer seriously restricts further condensation of the steam. That is to say, as the steam condenses gradually in the condenser tube, the nitrogen diffusion layer appears and becomes thicker and thicker along the axial direction, only passing through which by way of convection

or diffusion steam can be condensed on the liquid film. The thermal resistance of nitrogen diffusion layer has become the primary factor to prevent further condensation of steam. Moreover, with the increment in inlet NCGMFs, steam condensation becomes more difficult. The strengthening measure is to enhance the gas–liquid disturbance in the condenser tube, to accelerate the removal of the condensate, and to thin or destroy the thickness of nitrogen diffusion layer which is the most important factor affecting the steam condensation characteristics.

5.2 Comparison of characteristics between HMSHC and HCCC

Next taking the HCCC as a reference, the steam condensation enhancement characteristics inside the HMSHC formed only by infixing a multi-start helical channel component into the condenser tube of HCCC mentioned earlier were experimentally investigated, and compared to that of the HCCC under the same experimental conditions. The comparison of the average CHTCs between the HMSHC and the HCCC under same experimental conditions is demonstrated in Figure 13. Figure 14 displays the comparison of the outlet CMFRs between the HMSHC and the HCCC under same experimental conditions. Figure 15 shows the comparison of the overall SCPDs between the HMSHC and the HCCC under the same experimental conditions.

In Figures 13 and 14, it can be concluded by comparison that, under same experimental conditions, when the mass flowrate of the cooling water changes from 2,500 to

Figure 13: Comparison of average CHTCs between HMSHC and HCCC under same experimental conditions.

Figure 14: Comparison of outlet CMFRs between HMSHC and HCCC under same experimental conditions.

4,000 kg h⁻¹ with an increment of 500 kg h⁻¹, when inlet nitrogen mass fraction changes separately from 0 to 2, 5, 7, and 10%, as far as the relative ratio of the whole experimental range, the average CHTCs of the HMSHC is approximately 2.35 times as much as that of the HCCC, and the outlet CMFRs of the HMSHC is approximately 1.25 times as much as that of the HCCC. It is noticeable that the above two performance indicators of the HMSHC are significantly better than that of the HCCC under same experimental conditions. Similarly, in Figure 15, it can also be concluded by comparison that the overall SCPDs of the HMSHC is approximately 1.16 times as much as that of the HCCC. The reinforcement mechanism of the HMSHC as follows: the decrease in the steam-side

Figure 15: Comparison of overall SCPDs between HMSHC and HCCC under same experimental conditions.

equivalent diameter improves significantly the steam-side speed, and accelerates the removal of the condensate, and undoubtedly thins the thickness of nitrogen diffusion layer. The use of the multi-start helical channels changes the steam flow direction, and prolongs the time of steam condensation. The secondary circulation generated in the multi-start helical channels also strengthens the disturbance, and even destroys the thickness of nitrogen diffusion layer, which would greatly promote the further condensation of the steam ultimately under the comprehensive function of various factors. While the reason for the enlargement of the overall SCPDs inside HMSHC is mainly due to more steam condensation and higher friction pressure loss.

Table 2: Summary of steam condensation characteristics inside HMSHC and HCCC

Characteristic	HCCC	HMSHC
Condensation type	Film condensation	Film condensation
Channel type of steam condensation	HCCC	HMSHC
Pressure of inlet steam (MPa)	0.7	0.7
Mass flowrates of inlet steam (kg h ⁻¹)	65	65
Equivalent diameter of steam channel (mm)	50	10
Specific mass flux of inlet steam (kg m ⁻² s ⁻¹)	8.0	198
Channel type of cooling water convection	Annular interlayer	Annular interlayer
Mass flowrates of cooling water (kg h ⁻¹)	2,500–4,000	2,500/4,000
Equivalent diameter of cooling water channel (mm)	23	23
NC gas type	Nitrogen	Nitrogen
Mass fractions of inlet NC gas (%)	0, 2, 5, 7, and 10	0, 2, 5, 7, and 10
Average CHTCs (W m ⁻² K ⁻¹)	2.157–5.294	4.311–11.017
Outlet CMFRs (kg h ⁻¹)	24.887–32.933	30.271–38.381
Overall SCPDs (MPa)	10.455–31.019	13.464–33.961
Performance evaluation factor of average CHTCs	—	2.02
Performance evaluation factor of outlet CMFRs	—	1.08

5.3 Performance evaluation factor of HMSHC

Finally, the performance evaluation factor was used to evaluate the comprehensive performance of the HMSHC in the above specific experimental scope. The performance evaluation factor h_{PEC} of the average CHTCs $\bar{h}_i$ is shown in equation (13), and the performance evaluation factor $\dot{m}_{\text{PEC}}$ of the outlet CMFRs $\dot{m}_{\text{oc}}$ is shown in equation (14).

$$h_{\text{PEC}} = \frac{(\bar{h}_i)_e/(\bar{h}_i)_r}{(\Delta P_{\text{io}})_e/(\Delta P_{\text{io}})_r}, \quad (13)$$

$$\dot{m}_{\text{PEC}} = \frac{(\dot{m}_{\text{oc}})_e/(\dot{m}_{\text{oc}})_r}{(\Delta P_{\text{io}})_e/(\Delta P_{\text{io}})_r}, \quad (14)$$

where the subscript “r” is the abbreviation of “reference”, here HCCC is taken as reference. The subscript “e” is the abbreviation of “enhancement”, here it refers to the HMSHC. The overall SCPDs between the inlet and outlet ΔP_{io} is the basis of the comparison. The comparative analysis results showed that the performance evaluation factor h_{PEC} of the average CHTCs inside the HMSHC is approximately 2.02, and the performance evaluation factor $\dot{m}_{\text{PEC}}$ of the outlet CMFRs inside the HMSHC is approximately 1.08. The performance evaluating values are reasonable. The conclusion is that the HMSHC can indeed improve steam condensation characteristics to varying degrees, but the overall SCPDs inside the HMSHC will increase correspondingly. Table 2 is a summary of steam condensation characteristics inside the HMSHC and the HCCC under the same experimental scope.

6 Conclusion

To study the steam condensation characteristics in the HMSHC, under given steam pressure, cooling water mass flowrates, and NCGMFs conditions, the experimental investigation of steam condensation inside the HMSHC is performed, and the performance evaluation factor in the HMSHC were calculated, and the reinforcement mechanism of steam condensation in the HMSHC were analyzed. The main conclusions are as follows:

- (1) Although the symmetrical and non-uniform distribution characteristics of the liquid film in the axial and circumferential directions in the HCCC, seven thermocouples on each row along the direction of steam flow, a total of 40 T-type thermocouples in six rows make the local temperature measurement more reasonable and make the average heat transfer calculation of steam condensation more accurate, at the top,

middle, and bottom part on the outer surface of the condenser tube and at the middle of the annular interlayer, respectively. It is found that the local temperature at the top part is higher than that at the bottom; however, the deviation gradually decreased along the direction of steam flow, especially at higher inlet NCGMFs.

- (2) In consideration of the complexity of steam/nitrogen condensation in the HMSHC, the experimental investigation of steam condensation in the HMSHC is based on that of steam condensation in the HCCC. Although the experimental Nu_{exp} of steam/nitrogen condensation in the HCCC are quite different from the predicted Nu_{cal} of Caruso's correlation, they are in good accordance with the predicted Nu_{cal} of the new fitting criterion in the study, less than $\pm 15\%$ for all data.
- (3) The degradation of three physical quantities clearly shows that nitrogen diffusion layer has a dramatic influence on steam condensation characteristics. In the HMSHC, taking the pure steam as a reference, the average CHTCs, the outlet CMFRs, and the overall steam condensations reduce by about 47, 12, and 22% when nitrogen mass fraction attains 10%, respectively. Inside the HCCC, by comparison to the pure steam, the average CHTCs, the outlet CMFRs, and the overall SCPDs reduce approximately by 58, 15, and 20%, separately. But for higher Re_m , the gas–liquid interfacial shearing stress likely weakens the negative effect of the NC gas. In addition, increasing the cooling water flowrate can entirely promote steam condensation.
- (4) The comparison results of steam condensation revealed that, under the specific experimental scope, the average CHTCs of the HMSHC is approximately 2.35 times as much as that of the HCCC, and the outlet CMFRs of the HMSHC is approximately 1.25 times as much as that of the HCCC, and the overall SCPDs inside HMSHC are about 1.16 times of that inside HCCC. The performance evaluation factor (equations [13] and [14]) is introduced to evaluate the comprehensive performance of the HMSHC for the above specific experimental scope. The calculation results showed that the performance evaluation factor h_{PEC} of the average CHTCs inside the HMSHC is approximately 2.02, and the performance evaluation factor $\dot{m}_{\text{PEC}}$ of the outlet CMFRs inside the HMSHC is approximately 1.08. The conclusion is that the performance evaluating values of the HMSHC are reasonable.

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