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Thermal analysis of internal condensation process in a horizontal tube of falling film evaporation

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ABSTRACT

Internal condensation in a horizontal tube of falling film evaporation is of great importance in the process of low-temperature multi-effect distillation (LT-MED). Thermal analysis of internal condensation in a horizontal tube is investigated within the practical operating parameters in a LT-MED desalination plant. The analysis takes into account of the effect of interfacial shear, axial pressure gradient, saturation condensation temperature, heat transfer temperature difference, and non-condensable gas (NCG) on heat transfer characteristics of internal condensation. It is done to obtain the exact correlations that different methods to calculate axial pressure drop gradient and heat transfer coefficient are compared. The results indicate that reducing condensation temperature and increasing temperature difference contribute to improving the condensation rate of unit length for certain values of the tube length and inlet steam velocity, and that the tube length depends on the heat transfer temperature difference. The analytical results also show that the effect of interfacial shear stress on condensation rate is important while that was usually neglected in previous research, and that very small mass fraction of NCG can significantly increase the tube length as the presence of NCG reduces local temperature difference along the tube length. Besides, an increase in tube length compensates the negative effect of interfacial shear stress and NCG on internal condensation.

Keywords: Internal condensation; Axial pressure drop gradient; Non-condensable gas; Horizontal tube of falling film evaporation; Tube length

1. Introduction

The desalination of sea water may effectively pave the way to resolve the water shortage in Chinese northern coastal regions. The processes of multi-stage flash (MSF), low-temperature multi-effect distillation (LT-MED) and reverse osmosis (RO) decide the prospective development of desalination [1]. LT-MED is a kind of MED desalination technology that uses falling film evaporation over the outer surface of a vertical column of horizontal steam-heated tubes. Because of the phase transitions on both sides of tubes, the heat transfer rate achieved in horizontal-tube falling film evaporation is considerably high and this gives it a distinctive advantage. The overall heat transfer coefficient of falling film evaporation is about double that of vertical-tube falling film evaporation, and three times that of flashing evaporation. Thus the heat transfer area can be greatly reduced [4–7]. Low running temperature is its

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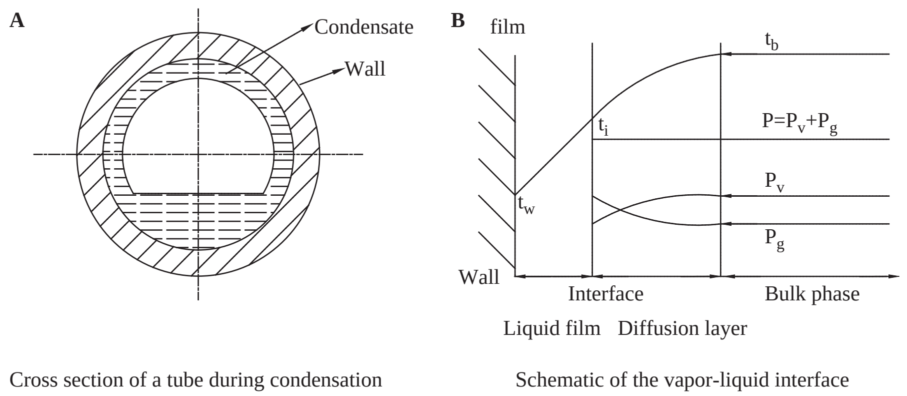

Fig. 1. Schematic of film condensation inside a horizontal tube in presence of NCG. (a) Cross section of a tube during condensation. (b) Schematic of the vapour-liquid interface.

dominating advantage that leads to reducing the possibility of scale formation. Recent developments in LT-MED have made this process compete technically and economically with that of MSF and RO [2]. The practical MED demonstration plant built by Sidem Company proved that its special energy consumption, about 5.5 kWh/t [3], is able to compete with than that of RO. MSF is the most popular process of thermal desalination plant. There are some practical problems resulting in higher running costs, among which the majority are related to high pressure and temperature in order to gain a satisfactory flashing and hence a worthwhile water yield. With an increase in temperature, the possibility of scale formation on the inside of the tubes increases. Thus the desalination plant needs to be cleaned periodically, which reduces the overall effectiveness of the MSF plant. In sum falling film evaporation over a horizontal tube is an energy-saving distillation technology.

Compared with most internal condensation process utilized in chemical, refrigeration and food industries, the heat transfer temperature difference of internal condensation in a horizontal-tube evaporator is small, about 1°C and the tube length is long, about 10-m long. Therefore the condensation axial pressure drop due to the interfacial shear stress between the condensation film and steam cannot be assumed as zero. Though many theoretical researches have been done on heat transfer of internal condensation of falling film evaporation, the effect of interfacial shear stress and non-condensable gas (NCG) on heat transfer was not taken into account. However the influence of NCG and interfacial shear stress may change the temperature difference along the tube length. Thus it is necessary to include the influence of NCG and interfacial shear stress on internal condensation and clarify their influence in order to provide a theoretical foundation for practical purpose.

2. Theoretical analysis of internal condensation

Condensation on a solid surface may take place in two different ways which are film-wise condensation and drop-wise condensation. For horizontal-tube falling film evaporation the internal condensation is film-wise condensation as shown in Fig.1 [8]. In this case when the liquid wets the surface, the condensate forms a continuous film covering the internal surface. The film flows over the surface under the action of gravity and interfacial shear stress caused by steam flow. The condensate flow pattern inside a tube is stratified as the condensate runs down the tube wall to form a layer at the bottom which will be swept along the tube by the steam flow. This simple model is complicated by the condensate film that forms on the tube wall and causes the stratified layer to grow. Laminar films are obtained when the gravity force is dominant and the Reynolds number in the liquid film remains low. The appropriate correlations are essential to provide a reliable set of performance results on the internal condensation. The analysis performed in the following is valid for selecting the appropriate correlations.

2.1. Comparison of heat transfer coefficient correlations of internal condensation

There appears to be some investigations on heat transfer coefficients of internal condensation in a horizontal tube. The research work [9–13] was carried out under ambient pressure and their data were not adequate. Akers [14] developed a physical model to regard the two-phase flow issue as the single-phase one by introducing an equivalent mass rate to calculate the effect of heating steam and condensate on the condensation process. The assumption was based on Nusselt's theory on film condensation [15]. It was assumed that the flow in the condensed film was laminar, the interfacial shear stress force was negligible, a linear temperature profile existed within the film and temperature at the gas liquid interface equals to the saturation temperature of pure steam at the chosen pressure. An empirical correlation of condensation heat transfer coefficient inside a horizontal tube was suggested by Shah [16] who believed that the two-phase flow heat transfer coefficient inside a tube was modified by correction coefficient based on the single-phase flow. The correction coefficient was the function of steam quality and steam pressure inside a tube. The two distinct condensation mechanisms were predicted for accurate estimation of heat transfer coefficient of internal condensation, corresponding to the annular and stratified flow patterns [17]. Thus flow patterns correspond to three kinds of flowing states: gravity-controlled flow state (stratified flow), shear-controlled flow state (annular flow) and combined gravity and shear-controlled flow state. The heat transfer correlation of internal condensation inside a horizontal tube was given for each flow state. Xu [18] conducted an experiment of falling film evaporation with various operation parameters and an experimental correlation was given, which accounted for the effects of liquid load, tube diameter, evaporation temperature, condensation temperature difference and inlet steam flow velocity on condensation process.

In order to determine the exact one used in a horizontal-tube falling film evaporator for LT-MED, a graphical comparison of local heat transfer coefficients of internal condensation is shown in Fig. 2. All the operating parameters and the dimensions of the horizontal tube are the practical ones at Huanghua LT-MED plant in China [19]. The dimensions include the tube inner diameter, 24 mm, and the length of the tube, 9.65 m. It can be clearly seen that the correlations provide quite different results. According to the calculated results in Fig. 2, the value of Schlunder's correlation is much higher than that of other correlations. Schlunder's correlation is selected as our simulation model. As heat transfer coefficient is obtained based on different flow states in Schlunder's correlation, it describes the heat transfer process of internal condensation accurately. The most important is that its result predicts the practical data with reasonable accuracy [19].

2.2. Condensation axial pressure drop gradient

The analysis of condensation axial pressure drop due to interfacial shear stress was considered by McAdams et al. [20]. They suggested a homogeneous flow model in which the axial pressure drop gradient along the length of the tube was gained for the two-phase flow inside a tube. Lockhart [21] proposed the phase-separation model to evaluate the axial pressure drop gradient of the two-phase flow. They assumed that the axial pressure drop gradient of the two-phase flow was simplified by introducing the equivalent mass rate of liquid or steam flow. Chisholm [22] developed the phase-separation model and proposed simple and accurate expressions to calculate the corrected coefficients. Friede [23] suggested a correlation to further improve the accuracy of calculated axial pressure drop gradient. Compared with other separated-phase models his results showed a deviation of 40–50%.

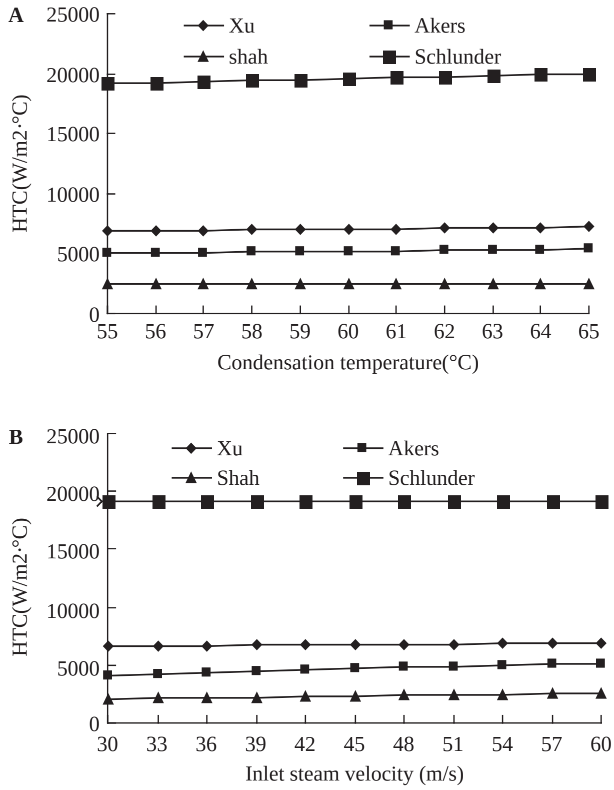

Fig. 2. Comparison of local heat transfer coefficients of internal condensation. (A) Outlet steam quality 0.15, inlet steam velocity 55 m/s and wall sub-cooling 1°C. (B) Saturation temperature 55°C, outlet steam quality 0.15 and wall sub-cooling 1°C.

The comparison of axial pressure drop gradient calculated by the above correlations is presented in Fig. 3 with respect to the outlet steam quality, inlet steam velocity, condensation temperature and wall sub-cooling. Fig. 3 shows that the calculated result of Friedel's correlation differs greatly from the others. As one of the most important characters of horizontal-tube falling film evaporation is small temperature difference of heat transfer for the internal condensation, the Friedel's correlation does not work obviously. For the axial pressure drop gradient is relatively small, together with the practical data [19], the Lockhart correlation is chosen as our simulation model.

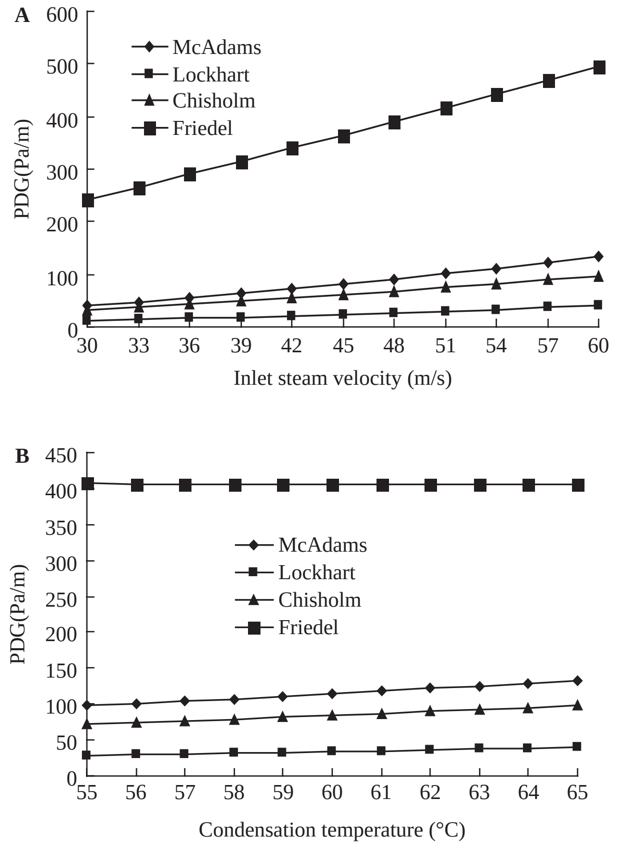

Fig. 3. Comparison of axial pressure drop gradient of internal condensation. (a) Outlet steam quality 0.15, condensation temperature 55°C and wall sub-cooling 1°C. (b) Outlet steam quality 0.15, velocity of inlet steam 55 m/s and wall sub-cooling 1°C.

3. Mathematical models

3.1. Heat transfer coefficient of pure steam condensation inside a horizontal tube

According to the superficial velocity of gas, j_g^+, the mathematical model of local heat transfer coefficient, α, is given for the corresponding three flowing states which include stratified flow, annular flow and transition flow between the stratified and annular flow [17].

$$j_g^+ < 0.5 \text{ the stratified flow dominates } \alpha = \alpha_{an}, \tag{1}$$

$$j_g^+ \geq 1.5 \text{ the annular flow dominates } \alpha = \alpha_{str}, \tag{2}$$

$$\begin{gathered} 0.5 \leq j_g^+ \leq 1.5 \text{ the transition flow dominates} \\ \alpha = \alpha_{an} + (j_g^+ - 1.5)(\alpha_{an} - \alpha_{str}), \end{gathered} \tag{3}$$

$$j_g^+ = \frac{Gy}{(gd\rho_v\rho_l)^{1/2}}. \tag{4}$$

(1) Stratified flow

$$\alpha_{an} = \Omega\left(\frac{\lambda_l^3(\rho_l - \rho_\nu)g\gamma}{\lambda_l d(t_i - t_w)}\right)^{1/4}. \tag{5}$$

(2) Annular flow

$$\alpha^+ = \frac{\alpha_{str}}{\lambda_l}\left(\frac{\nu_l^2}{g}\right)^{1/3}, \ \mathrm{Re_c} = 50, \tag{6}$$

$$\alpha^+ = 1.41 R_e^{-(1/2)}(\tau_1^+)^{1/2}, \quad \mathrm{Re} < \mathrm{Re_c}, \tag{7}$$

$$\frac{\alpha^+}{(\tau_1^+)^{1/2}} = \left(\left(\frac{1.41}{R_e^{1/2}}\right)^m + \left(\frac{0.071 P_r^{1/2}}{R_e^{\frac{1}{4}}}\right)^m\right)^{1/m}, \quad \mathrm{Re} > \mathrm{Re_c}. \tag{8}$$

3.2. Axial pressure drop gradient of liquid-steam two-phase phase flow

The phase-separation model was proposed to evaluate the axial pressure drop gradient of the two-phase flow in terms of the equivalent mass rate of steam flow [19]:

$$\frac{dp}{dz} = \Phi_{go}^2\left(\frac{dp}{dz}\right)_{go}, \tag{9}$$

where

$$\left(\frac{dp}{dz}\right)_{go} = \frac{\lambda_{go}}{d}\frac{G^2}{2\rho_v}, \tag{10}$$

$$\Phi_{go}^2 = \left(\frac{\rho_v}{\rho_l} + X\left(1 - \frac{\rho_l}{\rho_g}\right)\right)\left(\frac{\mu_v}{\mu_l} + X\left(1 - \frac{\mu_l}{\mu_v}\right)\right)^{-1/4}, \tag{11}$$

$$\lambda_{go} = 0.3164\ \mathrm{Re}_g^{-1/4} \tag{12}$$

3.3. Condensation inside a horizontal tube in presence of NCG

The governing equation for energy conservation equation at the interface shown in Fig.1b can be written as

$$\alpha(t_i - t_w) = \alpha_g(t_b - t_i) + \dot{m}r. \tag{13}$$

The condensation rate of steam at the interface can be described as

$$\dot{m} = \rho_g \beta_g \frac{y_{i,v} - y_v}{y_{i,v} - 1}. \tag{14}$$

The mass concentration of steam at the interface can be calculated as [21]

$$y_{i,v} = \frac{p_{i,v}}{p_{b,v}\Phi_v}. \tag{15}$$

3.4. Solution algorithm

The solution algorithm stars with the assumption that the temperature of tube wall keeps constant during the condensation process. With the above chosen correlations in controlled volume along the tube length, the temperature of condensation film and condensation rate is calculated. Therefore the variation of the outlet steam quality, heat transfer temperature difference of internal condensation, the tube length, inlet mass concentration of NCG and condensation temperature is obtained.

4. Results and discussion

4.1. Effect of tube length on outlet steam quality

It is shown in Fig. 4 that the effect of tube length on outlet steam quality. The results are presented for different temperature difference, Δt, between inlet steam and tube inside surface and for a particular condensation saturation temperature, 65°C. It can be seen that the outlet steam quality decreases with an increase in tube length and Δt.

With an increase in Δt, the heat transfer rate for the unit length, q, increases while the local heat transfer coefficient, h, reduces. As the portion of condensation rate contributed from q dominates, the outlet steam quality reduces with an increase in Δt. An increase in the tube length, corresponding to an increase in the heat transfer area, results in more steam being condensed. It is worth noticing that there are not the relevant values of outlet steam quality for $L = 9$ and $L = 10$ when Δt is beyond 1.2°C. This is because the steam is condensed completely before it reaches the outlet of the tube. Therefore the temperature difference is an important factor to decide the tube length.

Fig. 5 reflects the effect of condensation temperature on the outlet steam quality. The outlet steam quality increases with an increase in condensation temperature. This is mainly because the steam density increases with an increase in condensation temperature, which leads to an increase in the inlet steam mass rate.

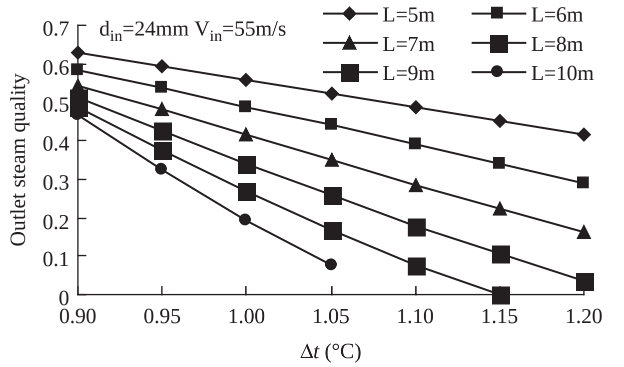

Fig. 4. Effect of tube length on outlet steam quality with different temperature difference.

4.2. Effect of interfacial shear stress and NCG on tube length

For given outlet steam quality three kinds of situations are compared to analyse the effect of outlet steam quality on tube length. The situations include the process of pure condensation, combined pure condensation with interfacial shear stress and combined pure condensation with interfacial shear stress and NCG.

In Fig. 6 the comparison among the three ones is done in terms of given outlet steam quality $X_{out} = 0.2$, condensation temperature and Δt. It is clearly seen that the calculated tube length in Fig. 6b is longer than that in Fig. 6a. The difference is due to the effect of interfacial shear stress on condensation rate which was usually regarded as negligible. The comparison between Fig. 6a and Fig. 6b proves that the interfacial shear stress is an important factor on internal condensation. When Fig. 6b is compared with Fig. 6c, it can also be seen that the presence of even very small mass fraction of NCG, 0.1%, significantly influences the tube length. When steam condenses in the presence of NCG along the tube length, the local temperature difference reduces due to an increase in local partial pressure of NCG and a decrease in local partial pressure of steam.

Fig. 7 shows the calculated tube length for different mass fraction of NCG. The tube length increases

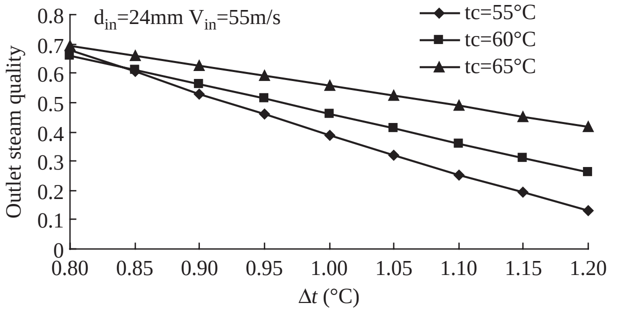

Fig. 5. Effect of condensation temperature on outlet steam quality with different temperature difference for $L = 5$ m.

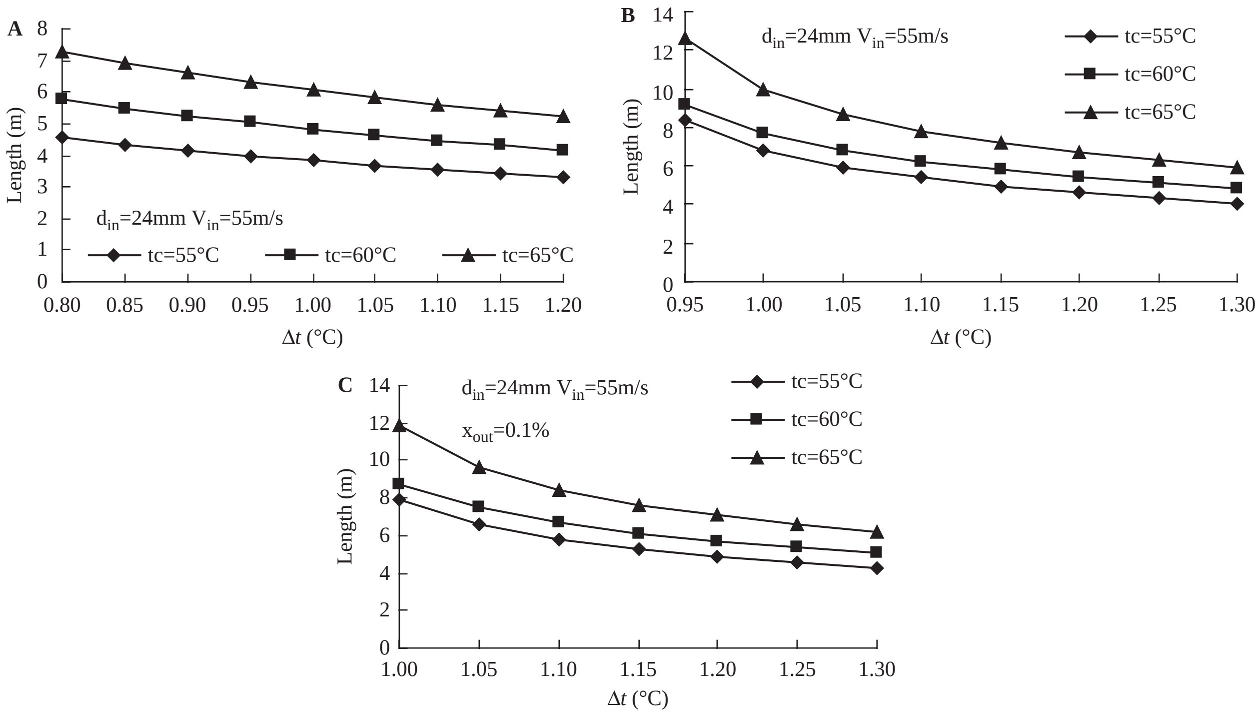

Fig. 6. Variation of tube length at different condensation temperature and temperature difference for given outlet steam quality $X_{out} = 0.2$. (a) Pure condensation. (b) Combined pure condensation with interfacial shear stress. (c) Combined pure condensation with interfacial shear stress and NCG.

obviously with an increase in mass fraction of NCG. It also can be seen that there is no corresponding tube length for $X_{NCG} = 0.3\%$ and $\Delta t < 1.1$°C. This is mainly because the local temperature difference becomes zero before the heating steam reaches the exit. Thus only certain part of the heat transfer area is used for heat transfer. The analytical result demonstrates that the mass fraction of NCG is one of the most important factors to decide the tube length.

The variation of the tube length at different Δt and outlet steam quality for three situations is shown in Fig. 8. The tendency of the tube length in the three situations is identical in terms of Δt and outlet steam quality. The tendency is that the high outlet steam quality corresponds to the long tube length. The calculated tube length in Fig. 8a is shorter than the corresponding one in Fig. 8b and Fig. 8c. It can be seen that the varying rate of tube length in Fig. 8a is approximately linear while that in Fig. 8b and Fig. 8c is mild, not as steep as in Fig. 8a. The main reason is that the effect of interfacial shear stress and NCG on internal condensation is compensated by increasing the tube length.

5. Conclusions

The analysis presented in this paper has investigated the thermal and hydrodynamic characteristics of a horizontal tube with an internal condensing steam flow. The correlations of heat transfer coefficient and interfacial shear stress of internal condensation have been compared and evaluated in order to select the correlations for simulation models. The selected models have been used to illustrate how various parameters affect the process of internal condensation. The calculation and analysis takes into account the effect of interfacial shear stress, NCG, outlet steam quality,

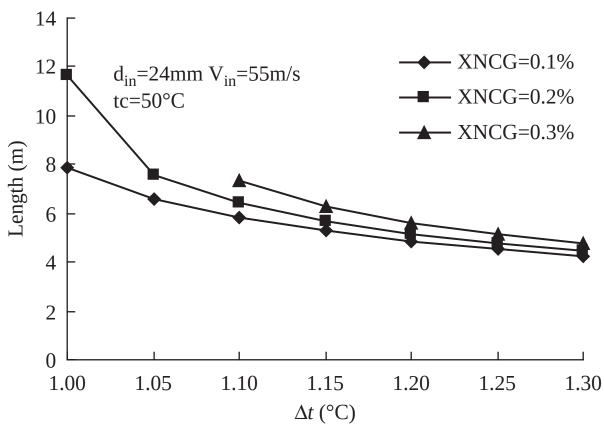

Fig. 7. Variation of the tube length at different mass fraction of NCG and temperature difference for given outlet steam quality$X_{out} = 0.2$.

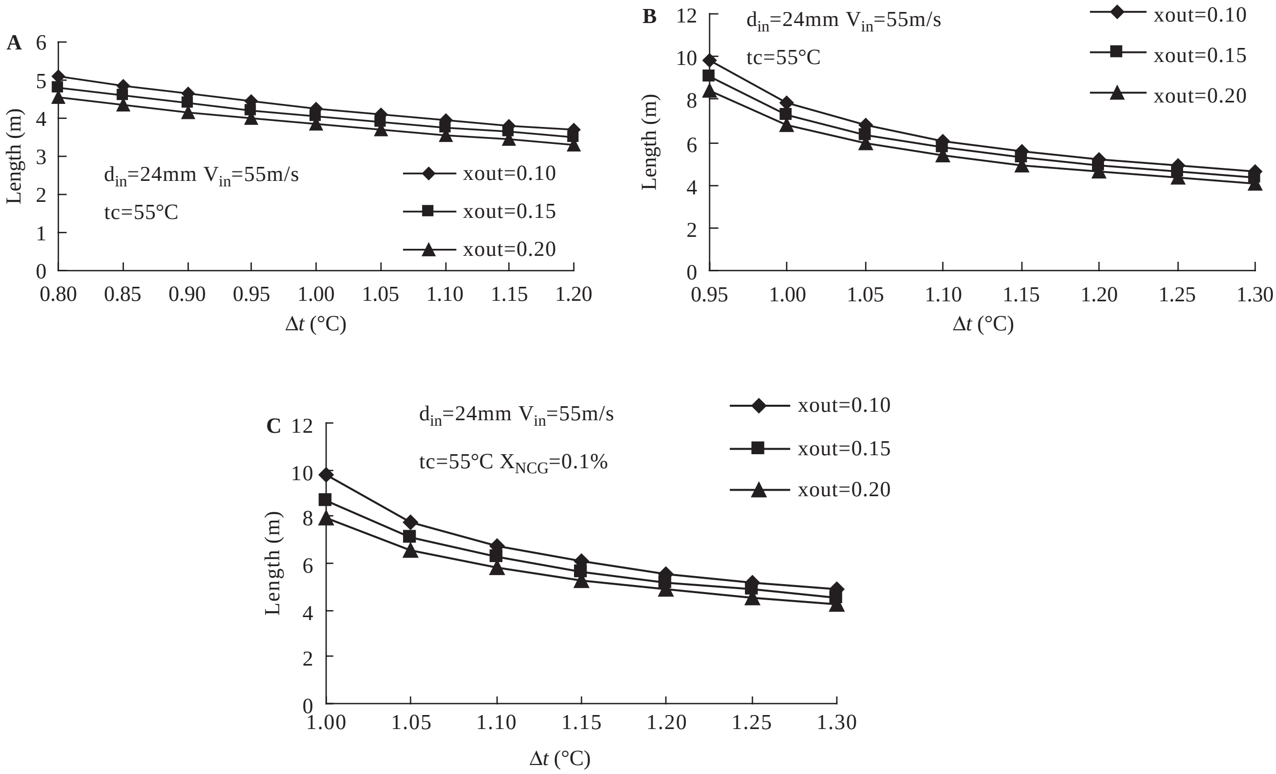

Fig. 8. Variation of the tube length at different temperature difference and outlet steam quality for given condensation temperature $t_c = 55°C$. (a) Pure condensation. (b) Combined pure condensation with interfacial shear stress. (c) Combined pure condensation with interfacial shear stress and NCG.

condensation temperature, heat transfer temperature difference on the heat transfer process of internal condensation. The results indicate that reducing condensation temperature and increasing temperature difference contributes to improving the condensation rate of unit length for certain values of the length of tubes and inlet steam velocity, and that the tube length depends on the temperature difference, i.e. the long tube corresponds to the low temperature difference. That is to say that the condensation temperature difference should be controlled in certain rang in order to avoid steam condensing completely before it reaches the exit of the tube. The analytical results also show that the effect of interfacial shear stress on condensation rate of internal condensation is important instead of being neglected, and the very small mass fraction of NCG can significantly increase the tube length as NCG which was usually not taken into account reduces the local temperature difference along the tube length. An increase in the tube length compensates the negative effect of interfacial shear stress and NCG on internal condensation.

Symbols

d	tube diameter, m
$\frac{dP}{dz}$	pressure gradient, Pa·m^{-1}
g	gravity acceleration, m·s^{-1}
j_g^+	superficial velocity of gas
m	condensation rate of steam, kg·s^{-1}
r	latent heat, J·kg^{-1}
X	steam quality
y	mass concentration of steam at the interface

Greek letters

α	local heat transfer coefficient, W·m^{-2}·K^{-1}
β	mass transfer coefficient in the gas phase, m·s^{-1}
λ	thermal conductivity, W·m^{-1}·K^{-1}
Φ	fugacity coefficient

Subscripts

b	bulk phase
i	interface
g	non-condensable gas
l	liquid phase
v	steam phase
w	wall

References

[1] R. Rautenbach, J. Widua and S. Schafer, Reflections on desalination processes for the 21st century, Proceedings of the IDA world congress on desalination and water sciences, Abu Dhabi, UAE (1995) 117–136.

[2] H.T. El-Dessouky and H.M. Ettouney, Multiple-effect evaporation desalination systems: thermal analysis, Desalination, 125 (1999) 259–276.

[3] N. Greco, A. Durante and F. Murat, Application of the multiple effect process at low temperature to a large sea water desalination plant, IDA World Congress on Desalination and Water Reuse, Washington, DC, (1991) l–16.

[4] A.S. Mohamed, Operational problems in the solar desalination plant and its remedies, Desalination, 93 (1993) 615–624.

[5] R.P. Hammond and D.M. Eissenbreg, Large-scale seawater distillation for Southern California, Desalination, 87 (1992) 69–73.

[6] A. Ophir, Low temperature multi-effect distillation for cogeneration yielding system, Desalination, 84 (1991) 85–101.

[7] V.N. Slesarenko, Seawater desalination in thin film plants, Desalination, 96 (1994) 173–181.

[8] C. De Ward and U. Lotz, Prediction of CO2 corrosion of carbon steel, Corrosion/93, NACE International (1993) 69.

[9] L. Zhang, H. Zheng and Y. Wu, Experimental study of a horizontal tube falling film evaporation and closed circulation solar desalination system, Renew. Energy, 28 (8) (2003) 1187–1199.

[10] M. Takada and J.C. Drake, Application of improved high-performance evaporator, Desalination, 45 (1983) 3–12.

[11] R. Rantenbach and B. Arzt, Waste heat utilization of large diesel engines by thermo-compression and low temperature multiple effect evaporation, Desalination, 44 (1983) 121–128.

[12] Z. Liu, Q. Zhu and Y. Chen, Evaporation heat transfer of falling water film on a horizontal tube bundle, Heat Trans.-Asian Res., 31(1) (2002) 42–55.

[13] M. A1-Shammiri and M. Safar, Multi-effect distillation plants: state of the art, Desalination, 126 (1999) 45–59.

[14] W.W. Akers, H.A. Deans and O.K. Crosser, Condensing heat transfer within horizontal tubes, Chem. Eng. Progr., 54(10) (1958) 89–90.

[15] W. Nusselt, Die Oberflachenkondensation des Wasserdampfes. VDI Z. 60 (1916), 569–575.

[16] M.M. SHAH, A general correlation for heat transfer during film condensation inside pipes, Int. J. Heat Mass Transfer, 22 (1979) 547–556.

[17] Ernst U. Schlunder, Heat Exchanger Design Handbook, Hemisphere Publishing Corporation, 1983, pp. 472–473.

[18] Li Xu, Shiyong Wang, Shichang Wang and Yuxin Wang, Studies on heat-transfer film coefficients inside a horizontal tube in falling film evaporators, Desalination, 166 (2004) 215–222.

[19] Insititute of thermal engineering of Dalian University of technology, Technical report on big-scale LT-MED desalination plants, 2008.

[20] W.H. McAdams, W.K. Woods,, and L.C. Heroman, Vaporization inside horizontal tubes part 2:benzine-oit mixtures, Trans. ASME, 64 (1942) 193–200.

[21] P.W. Lockhart and R.C. Martinelli.,Proposed correlation of data for isothermal two-phase two-component flow in pipes, Chem. Eng. Pros., 45 (1) (1949) 39–48.

[22] D. Chisholm, A theoretical basis for the Lockhart-Martinelli correlation for two-phase flow, Int. J. Heat Transfer, 10 (1967) 1767–1778.

[23] L. Friedel, Improval friction pressure drop correlations for horizontal and vertical two-phase pipe flow, European Two-Phase Flow Group Meeting, Italy, 1979, Paper E2.