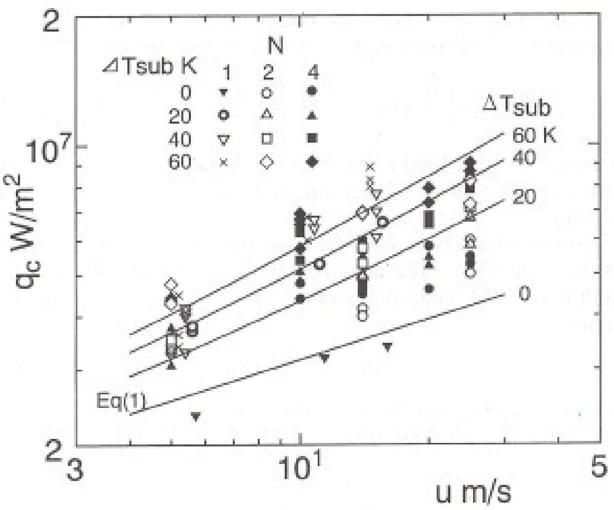

Fig. 3 Relationship between CHF and jet velocity for water at 0.1 MPa

60 K. A straight line in Fig. 3, for reference, is the CHF, which is calculated for the corresponding subcooling level from Eq. (1).

Figure 3 shows that an effect of subcooling on the CHF at the same subcooling level depends on the jet velocity, that is the CHF at the same subcooling level is enhanced with an increase in the velocity as shown by the slope of the line for the same subcooling predicted by Eq. (1), which becomes sharper with an increase in subcooling level. Incidentally, the CHF data for $\Delta T_{sub} = 0$ K are about 20–30 percent higher than those predicted by Eq. (1). The reason is not known.

The dependence of the CHF on subcooling and jet velocity may be understood easily from the change of the flow aspect and the CHF point when increasing heat flux to the CHF point.

4 Comparison of CHF Data With Eq. (1)

Figure 4 shows a relationship between the CHF data and the values predicted by Eq. (1), which are plotted against the subcooling level. It shows that the CHF data are in good agreement with the predicted values. In addition, 85 percent of the CHF data for the subcooled liquid can be predicted with an accuracy of ±20 percent while 96 percent of the data fall within a range of ±30 percent. Finally, for all the 121 CHF data points, we find a mean average of −1.85 percent, mean deviation of 11.5 percent, and standard deviation of 16.0 percent.

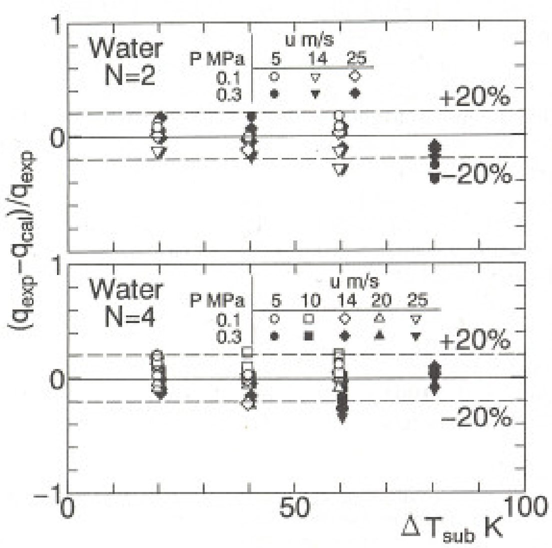

Fig. 4 Comparison of CHF data with Eq. (1)

Comparing accuracies of predicting the CHF data for both cases of the single jet and multiple jets, one notices that both CHFs are identically predicted with the same accuracy by Eq. (1).

5 Conclusions

Critical heat flux with multiple circular impinging jets has been measured by employing water at a subcooling up to $\Delta T_{sub} = 80$ K and velocity of 5 to 25 m/s.

1 Characteristics of CHF for both the single jet and multiple jets are similar, when focusing on the region controlled by each individual jet.
2 Equation (1) can predict the CHF data not only for the multiple jets but also for the single jet with the same accuracy.

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Effect of Fog Formation on Turbulent Vapor Condensation With Noncondensable Gases

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Nomenclature

c = molar density, mole m^{-3}
c_p = molar specific heat, J mole^{-1} K^{-1}
$\mathbb{D}$ = diffusion coefficient, m^2 s^{-1}
D = tube diameter, m
F = saturation line
h_{fg} = latent heat of condensation, J mole^{-1}
k = thermal conductivity, W m^{-1} K^{-1}
L = tube length, m
Le = Lewis number
l = characteristic length, m
M = mass of one kmole of substance, kg mole^{-1}
Nu = Nusselt number
P = pressure, Pa
Pr = Prandtl number
q = heat flux, W m^{-2}
Re = Reynolds number
Sc = Schmidt number

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Sh = Sherwood number
T = absolute temperature, K
x = mole fraction
θ = correction factor

Subscripts

b = bulk
c = diffusional
f = fog formation
g = noncondensables
i = condensate/gas interface
l = neutral (without suction and without fog formation)
s = sensible
tot = total
t = thermal
v = vapor

Superscripts

mf = including mass transfer (suction) and fog formation

Introduction

In a recent paper, Peterson et al. (1993) analyzed the turbulent vapor condensation in tubes and on plates in the presence of noncondensables. Experiments were furthermore performed with mixtures of a noncondensable gas and steam. A parameter $C_s/C_c = 7$ was introduced to match the experimental results and the theoretical model. This parameter was attributed to mist formation, as this process enhances sensible heat transfer and reduces condensation heat transfer in a condenser. Employing the model of Brouwers (1992), it will be demonstrated that the major part of this parameter can be derived from a basic consideration of combined heat and mass transfer. These transfer rates are affected by both fog formation and suction (i.e., vapor diffusion induced velocity).

Heat and Mass Transfer Model

First, the sensible heat transfer between gas mixture and condensate is discussed. The actual Nusselt number, Nu^{mf}, in case of suction and fog formation can be obtained by multiplying the neutral (i.e., zero mass flux and no fog) Nusselt number Nu_l by two correction factors (Brouwers, 1992)

$$\mathrm{Nu}^{mf} = \mathrm{Nu}_l\theta_t\theta_{tf} \tag{1}$$

with θ_t as correction factor for the effect of mass transfer (suction/blowing) on heat transfer (Brouwers, 1991), commonly referred to as the Ackermann correction:

$$\theta_t = \frac{\dfrac{c_{pv}\,\mathrm{Sh}_l}{c_p\,\mathrm{Le}\,\mathrm{Nu}_l}\ln\left(\dfrac{1-x_{vb}}{1-x_{vi}}\right)}{\exp\left(\dfrac{c_{pv}\,\mathrm{Sh}_l}{c_p\,\mathrm{Le}\,\mathrm{Nu}_l}\ln\left(\dfrac{1-x_{vb}}{1-x_{vi}}\right)-1\right)} \tag{2}$$

and the fog correction factor as

$$\theta_{tf} = \frac{1+\dfrac{h_{fg}}{c_p}\dfrac{1}{\mathrm{Le}}\dfrac{x_{vb}-x_{vi}}{T_b-T_i}\dfrac{\mathrm{Sh}_l}{\mathrm{Nu}_l}}{1+\dfrac{h_{fg}}{c_p}\dfrac{1}{\mathrm{Le}}\left.\dfrac{dF}{dT}\right|_{T_i}} \tag{3}$$

$F(T)$ represents the saturation line of water vapor, or $P_v(T)/P_{\mathrm{tot}}$ (in Eq. (7) of Peterson et al. (1993), P_i should read P_t). The mixture's specific molar heat c_p follows from $(1-x_{vb})c_{pg} + x_{vb}c_{pv}$ and $\mathrm{Le} = k/c\mathbb{D}c_p$. The sensible heat transfer from mixture to condensate then follows from

$$q''_s = \frac{\mathrm{Nu}^{mf}k}{l}(T_b - T_i) = \frac{\mathrm{Nu}_l k}{l}\theta_{tf}\theta_t(T_b - T_i) \tag{4}$$

Peterson et al. (1993) obtained a similar expression for the heat transfer, only $\theta_t\theta_{tf}$ was omitted (i.e., Nu^{mf} was set equal to Nu_l).

Now attention is focused on mass transfer by vapor diffusion to the condensate. The actual Sherwood number follows from multiplying the neutral Sherwood number by two correction factors

$$\mathrm{Sh}^{mf} = \mathrm{Sh}_l\theta_c\theta_{cf} \tag{5}$$

with θ_c as correction factor for the effect of mass transfer (suction/blowing) on mass transfer (Brouwers, 1991),

$$\theta_c = \frac{\ln\left[1-\dfrac{x_{vb}-x_{vi}}{1-x_{vi}}\right]}{-\dfrac{x_{vb}-x_{vi}}{1-x_{vi}}} \tag{6}$$

and the fog correction factor

$$\theta_{cf} = \frac{1+\left[\dfrac{h_{fg}}{c_p}\dfrac{1}{\mathrm{Le}}\dfrac{x_{vb}-x_{vi}}{T_b-T_i}\dfrac{\mathrm{Sh}_l}{\mathrm{Nu}_l}\right]^{-1}}{1+\left[\dfrac{h_{fg}}{c_p}\dfrac{1}{\mathrm{Le}}\left.\dfrac{dF}{dT}\right|_{T_i}\right]^{-1}} \tag{7}$$

The latent heat transfer from mixture to condensate then reads

$$q''_c = h_{fg}\frac{\mathrm{Sh}^{mf}c\mathbb{D}M_v}{l}\left(\frac{x_{vb}-x_{vi}}{1-x_{vi}}\right)$$
$$= h_{fg}\frac{\mathrm{Sh}_l c\mathbb{D}M_v}{l}\theta_{cf}\theta_c\left(\frac{x_{vb}-x_{vi}}{1-x_{vi}}\right) \tag{8}$$

Peterson et al. (1993) also used Eq. (8), including θ_c (suction), but without θ_{cf}. For turbulent flow in a tube they found an enhancement of Sh_l by a factor of 1.2, which they grant to suction and ripples. But Peterson et al. (1993) did actually include suction in their description of mass transfer. This can be verified by combining the two last factors on the right-hand side of Eq. (8) and applying Eq. (6). So, this enhancement of 20 percent can be attributed to ripples only.[2] It should be noted that this effect affects Sh_l and Nu_l to the same extent, so that it cannot be a reason for C_s/C_c being unequal to unity.

Equations (3) and (7) contain fog correction factors in mole fraction notation. Originally, the correction factors of Brouwers (1992) are based on an analysis with mass fraction notation. It can be easily verified that the same analysis with mole fraction notation will result in Eqs. (3) and (7).

For both turbulent vapor condensation in tubes and condensation on walls, the ratio of neutral Nusselt and Sherwood numbers can be expressed as

$$\frac{\mathrm{Sh}_l}{\mathrm{Nu}_l} = \mathrm{Le}^n \tag{9}$$

Peterson et al. (1993) mention $n = 0.35$ for forced convective turbulent flow in tubes and $n = 0.33$ for turbulent free convec-

[2] A part of this enhancement can also be attributed to entry effects. From Burmeister (1983) it follows that the Nusselt and Sherwood numbers are enhanced by a factor of $(1 + C\,D/L)$ for $\mathrm{Pr} \approx 1$ and $\mathrm{Sc} \approx 1$, with C ranging from 1.4 to 7, and $L/D \approx 24$ for the experiments by Peterson et al. (1993). Even for $C = 1.4$, a transfer augmention of 6 percent is obtained.

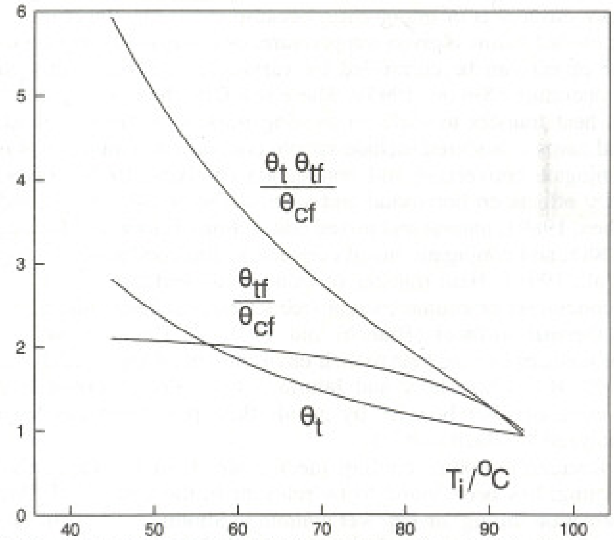

Fig. 1 Correction factors for fog formation and suction for mixtures of water vapor and air with T_b = 94°C, $x_{vb} = F(T_b) = 0.804$, and various interface temperatures T_i

tion along vertical plates. Combining Eqs. (1), (5), and (9) yields a ratio for the actual Sherwood and Nusselt numbers

$$\frac{\mathrm{Sh}^{mf}}{\mathrm{Nu}^{mf}} = \frac{\theta_c \theta_{cf}}{\theta_t \theta_{tf}} \mathrm{Le}^n \tag{10}$$

The analysis of Peterson et al. (1993), however, yields a ratio

$$\frac{\mathrm{Sh}^{mf}}{\mathrm{Nu}^{mf}} = \frac{C_c \theta_c}{C_s} \mathrm{Le}^n \tag{11}$$

Without fog formation and suction, Peterson et al. (1993) confirmed that $C_s/C_c = 1$, which is the result of the common analogy of heat and mass transfer. Due to fog formation, they put forward a C_s/C_c unequal to unity (the exact condition for and presence of fog formation will be verified later in this note). From Eqs. (10) and (11) it can be concluded that Peterson et al. (1993): (1) included θ_c, but not the Ackermann correction θ_t. This neglect is not allowed as both θ_c and θ_t are of the same order of magnitude since Le ≈ 1, $\mathrm{Nu}_l \approx \mathrm{Sh}_l$, and $c_{pv} \approx c_{pg} \approx c_p$ (θ_c and θ_t are equal if $k\,\mathrm{Nu}_l = c\mathbb{D}c_{pv}\,\mathrm{Sh}_l$); (2) corrected the effects of both fog formation and θ_t via $C_s/C_c = 7$. According to the analogy of heat and mass transfer this ratio should be equal to unity.

On the basis of Eqs. (10) and (11) it can be seen that

$$\frac{C_s}{C_c} = \frac{\theta_t \theta_{tf}}{\theta_{cf}} = \theta_t \mathrm{Le}^n \frac{x_{vb} - x_{vi}}{T_b - T_i} \left[\left. \frac{dF}{dT} \right|_{T_i} \right]^{-1} \tag{12}$$

whereby Eqs. (3), (7), and (9) have been inserted.

Model Application and Results

Now it is interesting to compute the right-hand side of Eq. (12) and verify whether this ratio approximates the value of 7. To this end, computations have been performed with $P_v(T)/[\mathrm{bar}] = \exp(11.6834 - 3816.44/(227.02 + T/[°\mathrm{C}]))$, taken from Reid et al. (1977), P_{tot} = 1.01325 bar (= 1 atm), T_b = 94°C, $x_{vb} = F(T_b) = 0.804$, Le = 0.85, n = 0.34, c_{pv} = 34 kJ/kmole K, c_{pg} = 29 kJ/kmole K. The interface properties (T_i, $x_{vi} = F(T_i)$) ranged from (45°C, 0.094) to (94°C, 0.804). In Fig. 1 the computed θ_t, θ_{tf}/θ_{cf}, and $\theta_t\theta_{tf}/\theta_{cf}$ are depicted versus T_i.

One can see that the correction factors deviate more from unity for smaller T_i, i.e., larger differences between bulk and interface properties. This would be expected as θ_t increases with larger difference between x_{vb} and x_{vi}, θ_t (and θ_c) tends to unity as x_{vb} tends to x_{vi}. Both θ_{tf} and θ_{cf} also deviate more from unity if the distance between (T_i, x_{vi}) and (T_b, x_{vb}), both situated on the saturation line, is increased and hence, the ratio of $(x_{vb} - x_{vi})/(T_b - T_i)$ and $dF/dT|$ in T_i is also increased (Brouwers, 1992). Furthermore, it can be seen that θ_t and θ_{tf}/θ_{cf} are of the same order of magnitude and contribute equally to their product. Figure 1 reveals that $\theta_t\theta_{tf}/\theta_{cf}$ tends to a value of 6, which corresponds closely to the general correlation value of 7 found by Peterson et al. (1993). This result yields the important conclusion that the factor found by these authors can be derived from known correction factors. Brouwers (1992) already demonstrated the applicability of these fog correction factors to laminar free and forced convective flow. Here then, the usefulness to turbulent free and forced convective flow is confirmed. Consequently, the film model approach can be recommended for future condenser computations.

For the remaining small difference between $\theta_t\theta_{tf}/\theta_{cf}$ and C_s/C_c of Peterson et al. (1993), besides common measurement uncertainties, a number of reasons is conceivable. For instance, they: (1) introduced an alternative description of heat transfer by replacing the bulk temperature by the saturation temperature. Although this approach is reasonable for saturated mixtures, it remains an approximate description; (2) replaced the saturation line by the Clausius–Clapeyron equation. This approach is allowed only in a narrow temperature and vapor pressure range; (3) did not account for the effect of fog formation on energy and vapor mass balances in the direction of flow. Including fog formation results in alternative incremental balances for the bulk temperature and vapor mole fraction in flow direction (Brouwers, 1992).

Furthermore, it should be noted that the film model as such, which is used in this note, also constitutes an approximate approach of heat and mass transfer. Brouwers (1992) found a discrepancy of about 4 percent between the laminar boundary layer model and the fog film model.

Finally, it should be proved that fog is really formed under all studied circumstances. To this end, the tangency condition can be employed (Brouwers, 1991, 1992), which predicts fog formation in a condenser if

$$\left. \frac{dF}{dT} \right|_{T_i} < \frac{\theta_c}{\theta_t} \frac{\mathrm{Sh}_l}{\mathrm{Nu}_l} \frac{x_{vb} - x_{vi}}{T_b - T_i} = \frac{\theta_c}{\theta_t} \mathrm{Le}^n \frac{x_{vb} - x_{vi}}{T_b - T_i} \tag{13}$$

where Eq. (9) has been substituted. This tangency condition has been verified for all situations pertaining to Fig. 1, yielding that this inequality is fulfilled for $T_i \le 88.1$°C ($x_{vi} \le 0.644$). This implies that fog formation takes place for $T_i \le 88.1$°C; thus the resulting θ_{tf}/θ_{cf} and $\theta_t\theta_{tf}/\theta_{cf}$ of Fig. 1 are valid in the range 45°C ≤ T_i ≤ 88.1°C. To achieve sufficiently large heat transfer rates, it is expected that T_i was much smaller than 88.1°C for the experiments performed by Peterson et al. (1993). The observed fog formation is therefore in agreement with the fog formation predicted by the tangency condition for 45°C ≤ T_i ≤ 88.1°C.

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