we find a mean average of $-1.85$ percent, mean deviation of 11.5 percent, and standard deviation of 16.0 percent.

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 $\Delta T_{\text{sub}} = 80$ 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.

References


Effect of Fog Formation on Turbulent Vapor Condensation With Noncondensable Gases

H. J. H. Brouwers

Nomenclature

$c = \text{molar density, mole m}^{-3}$

c_{p} = \text{molar specific heat, J mole}^{-1} \text{K}^{-1}$

$D = \text{diffusion coefficient, m}^{2} \text{s}^{-1}$

$D = \text{tube diameter, m}$

$F = \text{saturation line}$

$h_{fg} = \text{latent heat of condensation, J mole}^{-1}$

$k = \text{thermal conductivity, W m}^{-1} \text{K}^{-1}$

$L = \text{tube length, m}$

$Le = \text{Lewis number}$

$l = \text{characteristic length, m}$

$M = \text{mass of one mole of substance, kg mole}^{-1}$

$Nu = \text{Nusselt number}$

$P = \text{pressure, Pa}$

$Pr = \text{Prandtl number}$

$q = \text{heat flux, W m}^{-2}$

$Re = \text{Reynolds number}$

$Sc = \text{Schmidt number}$

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Sha = Sherwood number  
\( T \) = absolute temperature, K  
\( x \) = mole fraction  
\( \theta \) = 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 \( C_c/C_g = 7 \) 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, \( \text{Nu}_{mf} \), in case of suction and fog formation can be obtained by multiplying the neutral (i.e., zero mass flux and no fog) Nusselt number \( \text{Nu}_i \) by two correction factors (Brouwers, 1992)

\[
\text{Nu}_{mf} = \text{Nu}_i \theta_c \theta_{cf}
\]  

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

\[
\theta_c = \frac{c_p \text{ Sh}_i}{c_p \text{ Le} \text{ Nu}_i} \ln \left( \frac{1 - x_{ob}}{1 - x_{oi}} \right) 
- \exp \left( \frac{c_p \text{ Sh}_i}{c_p \text{ Le} \text{ Nu}_i} \ln \left( \frac{1 - x_{ob}}{1 - x_{oi}} \right) - 1 \right)
\]  

and the fog correction factor as

\[
1 + \frac{h_{fg}}{c_p} \frac{1}{\text{ Le} \frac{T_b - T_i}{\text{ Nu}_i}} \frac{x_{ob} - x_{oi}}{1 - x_{oi}}
\]  

\[
\theta_{cf} = \frac{1}{1 + \frac{h_{fg}}{c_p} \frac{1}{\text{ Le} \frac{dT}{dT_i}}} \]  

The latent heat transfer from mixture to condense then reads

\[
\text{q}_{cf} = h_{fg} \text{ Sh}_{mf} c \text{ D} \text{ M}_s \left( \frac{x_{ob} - x_{oi}}{1 - x_{oi}} \right)
\]

Peterson et al. (1993) also used Eq. (8), including \( \theta_i \) (suction), but without \( \theta_c \). For turbulent flow in a tube they found an enhancement of \( \text{Sh}_i \) 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. It should be noted that this effect affects \( \text{Sh}_i \) and \( \text{Nu}_i \) to the same extent, so that it cannot be a reason for \( C_c/C_g \) 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

\[
\frac{\text{Sh}_i}{\text{Nu}_i} = \text{Le}^n
\]

Peterson et al. (1993) mention \( n = 0.35 \) for forced convective turbulent flow in tubes and \( n = 0.33 \) for turbulent free convect...
Fig. 1 Correction factors for fog formation and suction for mixtures of water vapor and air with $T_r = 94°C$, $x_{wb} = F(T_b) = 0.804$, and various interface properties. This would be expected as $\theta_t$ increases with larger difference between $x_{wb}$ and $x_{ni}$, $\theta_t$, and $(\theta_t)$ tends to unity as $x_{wb}$ tends to $x_{ni}$. Both $\theta_f$ and $\theta_{cf}$ also deviate more from unity if the distance between $(T_r, x_{wb})$ and $(T_r, x_{wb})$, both situated on the saturation line, is increased and hence, the ratio of $(x_{wb} - x_{ni})/(T_r - T_i)$ and $dF/dT$ in $T_i$ is also increased (Brouwers, 1992). Furthermore, it can be seen that $\theta_t$ and $\theta_f$, $\theta_{cf}$ are of the same order of magnitude and contribute equally to their product. Figure 1 reveals that $\theta_t$ is a function of $\theta_f$ tends to a value of 6, which corresponds closely to the general correction 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 $\theta_t$, $\theta_f$, and $C_f/C_r$ 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

$$\frac{dF}{dT} \leq \frac{\theta_t}{\theta_f} \left( x_{wb} - x_{ni} \right) \left( \frac{dF}{dT} \right) \left( T_b - T_i \right)$$

where $\theta_t$ has been substituted. This tangency condition has been verified for all situations pertaining to Fig. 1, yielding that this inequality is fulfilled for $T_i \leq 88.1°C$ ($x_{wb} = 0.644$).

This implies that fog formation takes place for $T_i = 88.1°C$, thus the resulting $\theta_t/\theta_f$, and $\theta_t/\theta_{cf}$ of Fig. 1 are valid in the range $45°C \leq T_i \leq 88.1°C$. 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 $45°C \leq T_i \leq 88.1°C$.

References