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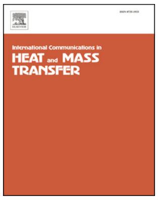

Development of heat and mass transfer model for condensation

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ABSTRACT

Divergence and the interfacial temperature deviation are the two main problems in condensation simulation with the Lee model. Based on the heat transfer analysis at the vapor-liquid interface, a correlation is revealed describing the relationship between interfacial temperature deviation and the model parameters, $q_i \approx (T_{sat} - T_i)(Ak_v)^{0.5}$ where $A = h_{fg} r \rho_v / T_{sat}$. With this correlation, the determination of the condensation frequency r is no longer empirical. Furthermore, the correlation indicates that the thermal conductivity of vapor plays an important role. Accordingly, an improved model is proposed amplifying the thermal conductivity of vapor in the phase interaction region. The model is verified with the Nusselt problem and the impacts of the model parameters are discussed and compared with the original Lee model. It is shown that the interfacial temperature deviation is reduced by the amplified thermal conductivity of vapor. The convergence is maintained by increasing both A and k_v synchronously. Verification is also obtained on the forced convection condensation of R134a. The correlation predicts a temperature deviation at 0.1 K and the numerical result successfully reaches 0.12 K.

1. Introduction

The vapor-liquid phase change process is highly concerned in both academia and industry. It is essential in heat exchangers such as evaporators, boilers and condensers. The VOF method [1] is well accepted in modeling multiphase flow, in which the vapor-liquid interface can be tracked via the conservation of volume fraction. The Lee model [2] is widely applied in modeling evaporation-condensation phenomena. The model defines the phase interaction term according to the temperature deviation from the saturated temperature. With the help of the Lee model, the heat exchanger design, especially for the refrigerants, has made a significant progress in predicting the performance of coil tubes [3], flattened tubes [4], mini-tubes [5–7], mini/micro-channels [8,9] etc.

The Lee model originates from the molecular kinetic theory. When the Hertz-Knudsen equation works together with the Clausius Clapeyron equation [10], the mass flux and the heat flux across the vapor-liquid interface can be yielded as

$$\dot{m}_i = \frac{2\kappa}{2-\kappa} h_{fg} \sqrt{\frac{1}{2\pi R T_{sat}}} \frac{\rho_v \rho_l}{\rho_l - \rho_v} \frac{T_{sat} - T}{T_{sat}} \tag{1}$$

$$\dot{q}_i = \dot{m}_i h_{fg} = \frac{2\kappa}{2-\kappa} h_{fg}^2 \sqrt{\frac{1}{2\pi R T_{sat}}} \frac{\rho_v \rho_l}{\rho_l - \rho_v} \frac{T_{sat} - T}{T_{sat}}. \tag{2}$$

R is the specific gas constant, J/kg-K; κ is the condensation coefficient defined as the ratio of the molecules absorbed by liquid to the total molecules impinged from vapor to liquid, $0 < \kappa \leq 1$.

Considering the application in VOF method, usually there is no real interfacial surface but an interfacial layer (where $0 < \alpha_v < 1$) as thick as several cells. Introducing an assumption that the subcooled vapor contains a number of nucleated liquid drops of which the surface-to-volume ratio is R_{sv}, the mass transfer rate of the interfacial cell becomes

$$\dot{m}_l = \alpha_v R_{sv} \dot{m}_i = \alpha_v R_{sv} \frac{2\kappa}{2-\kappa} h_{fg} \sqrt{\frac{1}{2\pi R T_{sat}}} \frac{\rho_l \rho_v}{\rho_l - \rho_v} \left(\frac{T_{sat} - T}{T_{sat}} \right). \tag{3}$$

Introducing a parameter r defined as

$$r = R_{sv} \frac{2\kappa}{2-\kappa} h_{fg} \sqrt{\frac{1}{2\pi R T_{sat}}} \frac{\rho_l}{\rho_l - \rho_v}. \tag{4}$$

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Nomenclature

A	coefficient defined in Eq. (9)
A_i	interfacial area, m^2
B	coefficient defined in Eq. (13)
F	volumetric surface tension force, N/m^3
$\vec{g}$	gravity, m/s^2
H	enthalpy, J/kg
h_{fg}	latent heat, J/kg
K	interface curvature, m^{-1}
k	thermal conductivity, W/m-K
k’	amplified vapor thermal conductivity, W/m-K
L	thickness of thermal interface layer, m
$\dot{m}_i$	mass flux through phase interface, kg/m^2-s
$\dot{m}_l$	volumetric mass transfer rate from vapor to liquid, kg/m^3-s
$\dot{m}_v$	volumetric mass transfer rate from liquid to vapor, kg/m^3-s
n	amplify factor of thermal conductivity
p	pressure, Pa
$\dot{q}$	volumetric energy source, W/m^3
$\dot{q}_i^*$	non-dimensional interfacial energy source
$\dot{q}_i$	interfacial energy source, W/m^2
R	specific gas constant, J/kg-K
R_{sv}	surface-to-volume ratio, m^{-1}
r	condensation frequency, s^{-1}
T	temperature, K
T^*	non-dimensional temperature
$\vec{u}$	velocity vector, m/s
x, y	Cartesian coordinate, m
x^*	non-dimensional Cartesian coordinate

Greek symbols

α	volume fraction
β	the A/k' value of CASE I
γ	the Ak' value of CASE I
κ	condensation coefficient, the ratio of absorbed molecules at phase interface
μ	viscosity, kg/m-s
ρ	density, kg/m^3
σ	surface tension, N/m

Subscripts

eff	effective
i	interfacial
l	liquid
sat	saturated
T	turbulence
v	vapor

Eq. (3) can be simplified and the Lee model for condensation is yielded as

$$\dot{m}_l = -\dot{m}_v = r\alpha_v\rho_v\frac{T_{sat}-T}{T_{sat}}, \quad \text{if } T<T_{sat}. \tag{5}$$

Correspondingly, for evaporation

$$\dot{m}_v = -\dot{m}_l = r\alpha_l\rho_l\frac{T-T_{sat}}{T_{sat}}, \quad \text{if } T>T_{sat}. \tag{6}$$

Therefore, the energy source term becomes

$$\dot{q} = \dot{m}_l h_{fg} = -\dot{m}_v h_{fg}. \tag{7}$$

Here r is called the evaporation/condensation frequency, with a unit of s^{-1}. The frequency is regarded as the key parameter in the Lee model, and is usually determined empirically. The experience showed that the proper r varies in different problems and even alters for different cases in the same problem. What's more, taking a brief scan on the literatures, it is learnt that the proper r in evaporation can be as low as 0.1 s^{-1} [11] while in condensation can be as high as 10^6 s^{-1} [9]. From Eqs. (5) and (6), it is clear that the larger the temperature difference is, the larger the mass source term is. In other words, when r is fixed, the intensity of the phase change highly depends on the temperature difference. A simplified interfacial energy source is adopted by researchers, i.e.

$$\dot{q} = A(T_{sat}-T). \tag{8}$$

Zhang et al. [12] set the coefficient A at 10^{20} when modeling capillary blocking in miniature tube condensation. Yuan et al. [13] investigated the condensation in plate-fin heat exchanger, setting $A = 10^{10}$. Eq. (8) can be considered as a simplified Lee model neglecting the contribution of volume fraction α. The fluid density and saturated temperature are both constant, then adjusting the multiplier A is equivalent to adjusting r.

Over the decades, the determination of coefficient r is highly empirical. Seen from Eq. (4), despite the physical properties there are two parameters left unknown, R_{sv} and κ. R_{sv} is difficult to measure and κ is even confusing. There are predecessors who tried to measure the condensation coefficient κ, but the yielded data for water ranges from 10^{-3} to 1, across three scales [14]. What's more, usually it is believed that the κ for condensation should be equal to the one for evaporation, but it is confirmed for water and R11 that the condensation one is almost 20% larger than that of evaporation [15, 16]. As a result, the determination of r via physics mechanism remains dim.

Rose reviewed the literatures on the condensation frequency and concluded that it is generally thought that the condensation coefficient is close to unity and the interface temperature drop is negligible for many cases except for liquid metals [17]. Taking κ as 1, Tanasawa calculated the water condensation at a temperature difference of 10 K, and the interfacial heat transfer coefficient is as large as 15.7 MW/m^2-K with an interfacial temperature drop of 0.007 K [10]. It means that the actual interfacial layer should be extremely thin so that it is not practical to apply such a small mesh size in VOF modeling. Therefore, the goal to determine r is rewritten as to find an r large enough to reduce the numerical yielded interfacial temperature drop to an acceptable level.

However, when modeling condensation, complains were frequently heard that only the high value of condensation frequency could sustain the vapor-liquid interface close to the saturated temperature. The problem is that the higher value, the higher risk to diverge. In this paper, a modification on the vapor thermal conductivity in two-phase region is proposed based on model analysis. The contribution of each parameter is discussed and a correlation is proposed to predict the interfacial temperature deviation. The improved model is proved better in both accuracy and convergence.

2. Interfacial heat transfer correlation

Upon the vapor-liquid interface, the energy equation can be reduced to a one dimensional thermal conduction problem by assuming that

① the time variation and the convection term are negligible compared with the latent heat;
② α_v stays 1 before arriving the interface.