Computational modeling of turbulent evaporating falling films

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A B S T R A C T

The primary objective of this study is to construct a computational model for turbulent, free-falling liquid films subjected to evaporative heating. The model is developed for two-dimensional axisymmetric flow on a vertical circular tube, with both the computational domain and operating conditions matching those of an experimental database for evaporating water films. Implemented in FLUENT, the model is used to predict variations of the evaporative heat transfer coefficient along the heated length, as well as profiles of eddy diffusivity, flow velocity, and temperature across the film. Energy transfer at the film's interface is captured successfully with the aid of a prior phase change model. The computational model predicts heat transfer coefficients for a broad range of Reynolds numbers that are in between predictions of two prior experimental correlations. The model predicts eddy diffusivity is fully dampened at the interface. The temperature profile across the liquid film features a steep gradient near the interface, which is attributed to turbulence dampening coupled with energy loss at the film's interface.

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1. Introduction

1.1. Falling-film heat transfer literature

Free-falling liquid films are found in a variety of industries, including chemical, pharmaceutical, and power generation. These films provide high heat transfer coefficients while capitalizing on gravity to achieve liquid motion. Heat exchangers utilizing falling films rely on either sensible or evaporative heating of the film. With sensible heating, the heat absorbed from the wall gradually increases the mean liquid temperature in the flow direction. On the other hand, evaporative heating is achieved once the film's interface reaches saturation temperature. Evaporating liquid films in practical applications are typically turbulent and capitalize upon the added mixing provided by interfacial waves to achieve very attractive heat transfer performance.

Most of the published falling-film studies concern laminar and turbulent fluid flow in adiabatic films. And, while studies concerning heat transfer to films are relatively sparse, far more data are available for sensible heating than evaporation. Table 1 provides a summary of popular falling-film correlations for both sensible heating and evaporative heating derived from measurements by different researchers. For evaporative films, early works include a study by Struve [8], who presented heat transfer data for R11. Chun

and Seban [6] performed fairly extensive measurements of evaporating water films and recommended heat transfer coefficient correlations for both laminar and turbulent films. Fujita and Ueda [9] also performed evaporative heating experiments with water at 1 atmosphere and compared their data to Chun and Seban correlations. Shmerler and Mudawar [7] performed experiments with turbulent free-falling water films and recommended an alternative correlation for the heat transfer coefficient.

1.2. Computational methods for phase change processes

Developing two-phase heat transfer facilities and performing experiments using different fluids and over broad ranges of operating parameters in order to measure heat transfer parameters is a very costly endeavor. This explains the present growing interest in utilizing computational methods to determine the same parameters. Use of computational tools to predict fluid flow and heat transfer in phase change system has been the subject of intense study only during the past two decades. Researchers have suggested different interfacial models to predict mass, momentum and heat transfer in phase change systems. Three main types of phase change models have been widely used for this purpose.

Early works conducted in the 1990s were based on the sharp interface model, which uses the Rankine–Hugoniot jump condition [10] for energy conservation at the interface. Micro-scale mass transfer is neglected and the liquid–vapor interface is maintained at saturation temperature. This allows mass transfer rate to be

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Nomenclature

A^+	constant in eddy diffusivity model
E	energy per unit mass
F	force
g	gravitational acceleration
h	heat transfer coefficient
h_E	heat transfer coefficient for evaporative heating, $q_w''/(T_w - T_{sat})$
h_E^*	dimensionless heat transfer coefficient for evaporative heating, $h_E v_f^{2/3}/(k_f g^{1/3})$
h_{fg}	latent heat of vaporization
h_H	heat transfer coefficient for sensible heating, $q_w''/(T_w - T_m)$
h_H^*	dimensionless heat transfer coefficient for sensible heating, $h_H v_f^{2/3}/(k_f g^{1/3})$
K	Von-Karman constant
k	thermal conductivity; turbulent kinetic energy
Ka	Kapitza number, $\mu_f^4 g/\left(\rho_f \sigma^3\right)$
L	length of heated portion of test section
M	molecular weight
$\dot{m}''$	interfacial mass flux
$\vec{n}$	unit vector normal to interface
p	pressure
Pr	Prandtl number
$Pr_{f,T}$	turbulent Prandtl number
Q	energy source term
q''	local heat flux normal to the wall
q_w''	wall heat flux
R	universal gas constant (8.314 J/mol K)
r	radial coordinate
Re	Reynolds number, $4\Gamma/\mu_f$
r_i	mass transfer intensity factor
S	volumetric mass source term
T	temperature
t	time
T_{sat}	saturation temperature

u	local x-direction velocity
u^*	friction velocity, $\sqrt{\tau_w/\rho_f}$
x	axial coordinate
y	distance perpendicular to the wall
y^+	dimensionless distance perpendicular to the wall, $y u^*/v_f$

Greek symbols

α	volume fraction, void fraction
δ	liquid film thickness
ε	dissipation rate of turbulent kinetic energy
ε_m	eddy momentum diffusivity
ε_h	eddy heat diffusivity
Γ	mass flow rate per unit film width
γ	accommodation coefficient in Schrage model
μ	dynamic viscosity
v	kinematic viscosity
ρ	density
τ	shear stress

Superscripts

$\rightarrow$	vector
$+$	dimensionless

Subscripts

c	condensation
$crit$	critical
e	evaporation
eff	effective
f	liquid
g	vapor
i	interfacial
m	mean
sat	saturation
w	wall

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determined from energy conservation at the interface according to the relation

$$q_i'' = -k_{eff} \nabla T_i \cdot \vec{n} = \dot{m}'' h_{fg}, \tag{1}$$

where $\dot{m}''$ [kg/m^2 s] is the mass flux due to phase change at the interface. The volumetric mass source term, S [kg/m^3 s], for the individual phases is determined from

$$S_g = -S_f = \dot{m}'' |\nabla \alpha_g| = \frac{k_{eff}(\nabla \alpha \cdot \nabla T)}{h_{fg}}, \tag{2}$$

where k_{eff} is the effective thermal conductivity determined from the volume fractions and thermal conductivities of the liquid and vapor. In effect, this model uses all energy crossing the interface for mass transfer.

The second popular approach is based on a model by Schrage [11], which in turn is based on the Hertz–Knudsen equation [12] that allows for interfacial jump in temperature and pressure, where $T_{sat}(p_f) = T_f \neq T_{sat}(p_g) = T_g$. The net mass flux across the interface, $\dot{m}''$ [kg/m^2 s], is determined by the difference between liquid to vapor and vapor to liquid mass fluxes,

$$\dot{m}'' = \frac{2}{2-\gamma_c} \sqrt{\frac{M}{2\pi R}} \left(\gamma_c \frac{P_g}{\sqrt{T_g}} - \gamma_e \frac{P_f}{\sqrt{T_f}} \right), \tag{3}$$

where $R = 8.314$ J/mol K is universal gas constant, γ the fraction of molecules transferred from one phase to the other during phase

change, and $1 - \gamma$ the fraction of molecules reflected at the interface. The subscripts c and e in Eq. (3) refer to condensation and evaporation, respectively, and $\gamma_e = 1$ and $\gamma_c = 1$ represent complete evaporation and complete condensation, respectively [13]. Many investigators use equal values of γ_c and γ_e by setting $\gamma_c = \gamma_e = \gamma$ in phase change simulations, and refer to γ as the "accommodation coefficient". Tanasawa [14] simplified Eq. (3) by setting the interfacial temperature equal to T_{sat}, and assuming the heat flux is linearly dependent on temperature jump between the interface and the vapor. For evaporation, their modified model is expressed as

$$\dot{m}'' = \frac{2\gamma}{2-\gamma} \sqrt{\frac{M}{2\pi R}} \frac{\rho_g h_{fg}(T - T_{sat})}{T_{sat}^{3/2}}, \tag{4}$$

where T_{sat} is based on local pressure, p, and the volumetric mass source term is determined from

$$S_g = -S_f = \dot{m}'' |\nabla \alpha_g|. \tag{5}$$

This model is applicable only to the liquid–vapor interface, and has been used mostly to tackle evaporating and condensing films, and film boiling.

The third popular approach is based on a phase change model proposed by Lee [15]. This model has been widely used in condensation studies, but is applicable to both condensation and boiling. The Lee model is based on the assumption that mass is transferred