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An elliptic two-phase numerical model of laminar film condensation from a steam-air mixture flowing over a horizontal tube

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ABSTRACT

A complete two-phase numerical model of film condensation from a steam-air mixture flowing downward over an isothermal horizontal tube is presented. The model uses the full 2D elliptic Navier-Stokes equations and predicts the full viscous flow and heat and mass transfer in the mixture and in the entire condensate film from the top of the tube to the falling film below the tube. The numerical model implements a dynamically moving non-orthogonal computational grid that tracks the phase interface sharply. An adaptive-grid Eulerian method is followed in which the phase interface is moved at the end of each time step. The model uses a segregated solution method based on a finite volume approach in which fundamental balances of mass, energy, and force are enforced accurately at the phase interface. The results from the new model are compared with available theoretical studies. Finally, new results are presented on the effects of free stream gas mass fraction, free-stream-to-tube temperature difference, upstream Reynolds number, and free-stream pressure on the condensate film development, the local and average heat transfer coefficients, and the total liquid mass flow rate.

1. Introduction

Condensation over horizontal tubes is an important process in heat exchangers in thermal power generation, chemical processing, desalination, refrigeration, and air conditioning. In the heat exchangers, the condensate appears on the tube surface as either droplets or a film, depending on the characteristics of the tube surface. Filmwise condensation is the most common form in engineering applications. Therefore, it has been investigated theoretically and experimentally since the milestone study of Nusselt [1] that dealt with laminar filmwise condensation of pure quiescent vapour on an isothermal horizontal tube. Subsequent theoretical investigations of film condensation over a horizontal tube considered condensation from pure vapour and mixture of vapour and non-condensing gas. It is well known that even small amounts of a non-condensing gas mixed with the vapour can significantly reduce the condensation rate.

In the pure vapour case, numerous theoretical investigations are available in the literature that involve single phase (liquid only) models [2–6] and two-phase (liquid and vapour) models [7–12]. In the case of vapour condensation from mixtures, fewer studies are available. In all those studies, a gas boundary layer in the mixture around the tube that encompasses both energy and momentum boundary layers was assumed where gas concentration varies from the free stream value. Surface tension effects were neglected in those studies.

Li and Peng [13] developed a mathematical model to study laminar condensation of downward flow of air-steam mixture on a horizontal tube using simplified equations based on boundary layer assumptions. The pressure gradient was determined assuming potential flow outside the mixture boundary layer. In the condensate film, inertia effects were omitted and the temperature was assumed to vary linearly. The gas conservation equation accounted only for advection and diffusion in the direction normal to the tube surface. A similarity solution approach was used in which the velocity distribution in each phase was obtained by integrating the corresponding momentum equation. Solutions were obtained for film thickness, local heat transfer coefficient, local condensate mass flux, and liquid-mixture interfacial temperature profile for a single tube with 14 mm outside diameter. The results presented were for upstream gas mass fraction, W_∞, values of 0.01, 0.05 and 0.1; for upstream velocity, U_∞, values of 0.1, 0.3 and 5.5 m s^{-1} (Re_D = 68.5, 204, and 3740); for upstream pressure, P_∞, values of 0.9, 1 and 1.1 atm; and for tube wall temperature, T_{wall}, values of 348, 353 and 358 K.

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Nomenclature

A	area, [m^2]
C_p	specific heat, [J kg^{-1} K^{-1}]
D	tube diameter, [m]
D^{ab}	binary diffusion coefficient, [m^2 s^{-1}]
Fr	Froude number, $(U_\infty^2/(gD))$
g	gravitational acceleration [m s^{-2}]
h	heat transfer coefficient, $(q''_{\text{wall}}/\Delta T)$[W m^{-2} K^{-1}]
$\bar{h}$	average heat transfer coefficient, $((\pi R)^{-1}\int_0^{\pi R} h\,ds)$ [W m^{-2} K^{-1}]
h_{fg}	latent heat of vapourisation, [J kg^{-1}]
Ja	Jakob number, $(C_{p,L}\Delta T/h_{fg})$
k	thermal conductivity [W m^{-1} K^{-1}]
$\dot{m}$	mass flow rate [kg s^{-1}]
n	normal direction
$\hat{n}$	local unit vector normal to the interface
Nu_s	local Nusselt number, $(h_s D/k_L)$
$\overline{Nu}$	average Nusselt number, $(\bar{h}D/k_L)$
N_i, N_j	number of control volumes in the i and j index directions, respectively
P	pressure [N m^{-2}]
Pr	Prandtl number, $(\mu C_p/k)$
q''	heat flux, [W m^{-2}]
R	tube radius, [m]
Re_L	liquid Reynolds number $(4\dot{m}_L/\mu_L)$
Re_D	mixture free stream Reynolds number $(\rho_M U_\infty D/\mu_M)$
s	coordinate along the tube surface and then below the tube along x
$\hat{s}$	local tangential unit vector at the interface
T	temperature, [K]
ΔT	free stream to wall temperature difference $(T_\infty - T_{\text{wall}})$, [K]
t	time, [s]
$\boldsymbol{T}$	stress tensor [N m^{-2}]
U	velocity in the x direction [m s^{-1}]
U_∞	mixture free stream velocity [m s^{-1}]
V	velocity in the y direction [m s^{-1}]
$\vec{V}$	velocity vector [m s^{-1}]
W	gas mass fraction, $m_g/(m_v + m_g)$
x, y	Cartesian coordinate directions, [m]

Greek Symbols

δ	film thickness [m]
ϵ_{ss}^{ϕ}	steady-state convergence criterion for field ϕ
θ	angle from the top of the tube [degrees]
μ	dynamic viscosity [kg m^{-1} s^{-1}]
ρ	density [kg m^{-3}]

Subscripts

e, w	referring to face quantities at the east and at the west, respectively
g	referring to gas
int	at the interface
L	referring to the liquid
M	referring to the mixture
max, min	maximum, minimum
sat	referring to saturation conditions
v	referring to the vapour
wall	referring to the wall
s	referring to the distance along the tube surface
t	tangential
∞	referring to the free stream or upstream conditions

Superscripts

$'$	correction
$''$	per unit area
n	current time step value
o	previous time step value

Chen and Lin [11] developed a numerical model to solve the problem of laminar film condensation from a downward-flowing mixture of steam-air on a horizontal tube. They studied the effects of gas mass fraction, upstream velocity of the mixture and upstream-to-tube temperature difference on film thickness and local heat transfer coefficient. The governing equations for both phases were formulated based on boundary layer assumptions. Potential flow was assumed outside the mixture boundary layer. Both thermal diffusion and viscous dissipation in the flow direction were neglected. Moreover, the effect of gravity in the mixture region was ignored. A finite difference approach was used to solve the boundary layer equations in the condensate film and the mixture regions using an approach that marches around the tube surface.

Tang et al. [14] presented a numerical model to solve the problem of film condensation on a horizontal isothermal tube that is exposed to a quiescent steam-air mixture. In general, their model did not differ significantly from that presented by Chen and Lin [11] in terms of the set of governing equations. Tang et al. included the body force in both phases and ignored the pressure variation around the tube; therefore, the potential flow assumption was eliminated. The numerical solutions were obtained for air mass fraction in the range $0.005 \leqslant W_\infty \leqslant 0.15$ and free-stream-to-wall temperature difference in the range, $5\text{ K} \leqslant \Delta T \leqslant 20\text{ K}$.

It is noted, therefore, that all theoretical studies that dealt with laminar film condensation from a vapour-gas mixture on a horizontal tube assumed a boundary layer flow in both the liquid and the mixture regions. A potential flow assumption was used at the edge of the mixture boundary layer in the studies where pressure variation was included. These models are parabolic in nature and the solution must be obtained by marching along the tube surface. These models do not predict the full viscous flow solution around the tube, and they are not valid after boundary layer separation.

A companion paper [12] describes a new, elliptic, sharp-interface model for laminar film condensation on a horizontal tube for downward flow of pure vapour. That model does not have the limitations of the marching solution approach. Furthermore, no potential flow assumption is made. The full two-dimensional Navier-Stokes equations are solved in both phases simultaneously for the whole liquid region (including flow after the tube) and the surrounding vapour region. The full viscous flow solution for the gas phase is performed with fundamental balances of mass, energy, and force applied accurately at the phase interface. A structured non-orthogonal computational grid is used that matches the shape of the phase interface. A mass-conservation-based approach is used to move the computational grid dynamically during the solution progression to match precisely the phase interface everywhere.

This article describes the extension of the previous work to the case of a gas-vapour mixture flowing over the tube and applies it to cases of steam-air flow. Calculation of the full viscous flow of