International Communications in Heat and Mass Transfer 94 (2018) 47–52

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Heat transfer in a falling laminar liquid film with in-depth radiation absorption☆

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ARTICLE INFO

Keywords:
Falling liquid film
Heat transfer
Thermal radiation

ABSTRACT

A heat transfer problem involving a steady-state falling liquid film along a vertical wall with an imposed constant heat flux on the liquid film surface and an in-depth thermal radiation absorption in the film layer is analyzed. The liquid film is assumed to be normal to the incident radiative heat flux, and the heat flux is assumed to be parallel and unidirectional. Nondimensionalized governing equations are formulated and solved numerically. Sample calculations are provided. The effects of pertinent dimensionless parameters on the heat transfer process are demonstrated. The calculated results reveal that the in-depth thermal radiation absorption would play a key role in the heat transfer in the liquid film.

1. Introduction

Heat and mass transfer in a falling liquid film along an inclined or vertical surface under the influence of gravity find many applications in chemical engineering processes, nuclear reactor safety, and fire protection engineering. Examples are wetted-wall columns, film reactors, evaporators, condensers, desalination, cooling of a heated surface, and thermal shielding of a surface from thermal radiation from fires [1–3]. Analytical and numerical studies have been reported in the literature (e.g., [4–13]). However, most, except [7], of the previous studies have not included the treatment of thermal radiation. In [7], the characteristics of heat, mass and momentum transfer of a water film falling over an inclined plate with solar radiant heating and water evaporation were investigated. The physical processes were highly coupled with conduction, convection with flow turbulence, diffusion, radiation, and phase change. In this work, heat transfer in a falling laminar liquid film with a radiative heat flux imposed on the liquid-gas interface and a simplified treatment of in-depth absorption of thermal radiation occurring in the liquid film without evaporation are examined. We encountered this problem while we were exploring the feasibility of using a flowing liquid film to cool the strong wall during experiments to study thermal responses of structural elements and systems to fires in a laboratory.

2. Problem formulation and analysis

Fig. 1 is a schematic representation of the problem considered. We limit our discussion here to a fully developed steady-state non-wavy laminar liquid film flow over a vertical surface. All thermo-physical properties of the liquid are assumed to be constant, and that the liquid film thickness is also assumed to be constant with negligible liquid evaporation over the domain of interest. The solid surface is maintained at uniform temperature T_w. Under these assumptions, the steady-state equation of motion for the falling liquid film with negligible viscous dissipation can be simplified to [4].

$$\mu_L \frac{d^2 v_z}{dy^2} = -\rho_L g \tag{1}$$

with the following boundary conditions

$$\text{At } y = 0, \qquad v_z = 0 \tag{2}$$

$$\text{At } y = \delta, \qquad \frac{dv_z}{dy} = 0 \tag{3}$$

Eq. (1) with the above two boundary conditions can be integrated to obtain the velocity distribution $v_z(y)$ in the falling film.

$$v_z = \frac{\rho_L g \delta^2}{2\mu_L}\left[2\left(\frac{y}{\delta}\right) - \left(\frac{y}{\delta}\right)^2\right] = v_{z,\max}\left[2\left(\frac{y}{\delta}\right) - \left(\frac{y}{\delta}\right)^2\right] \tag{4}$$

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https://doi.org/10.1016/j.icheatmasstransfer.2018.03.009

0735-1933/ Published by Elsevier Ltd.

Nomenclature

a	Liquid absorption coefficient
C_p	Liquid heat capacity
g	Gravitational acceleration
h	Convective heat transfer coefficient
k_L	Liquid thermal conductivity
q_e	External heat flux applied on the liquid film surface
$\overrightarrow{q_r}$	Radiative flux vector
T	Liquid film temperature
T_0	Liquid film temperature at $z = 0$
T_w	Wall temperature
T_∞	Ambient temperature
v_z	z-component velocity
$v_{z,\ \max}$	Maximum z-component velocity
$v_{z,\ m}$	Mean z-component velocity
y	y-direction
z	z-direction
α_L	Liquid thermal diffusivity
δ	Liquid film thickness
μ_L	Liquid viscosity
ν_L	Liquid kinematic viscosity
ρ_L	Liquid density

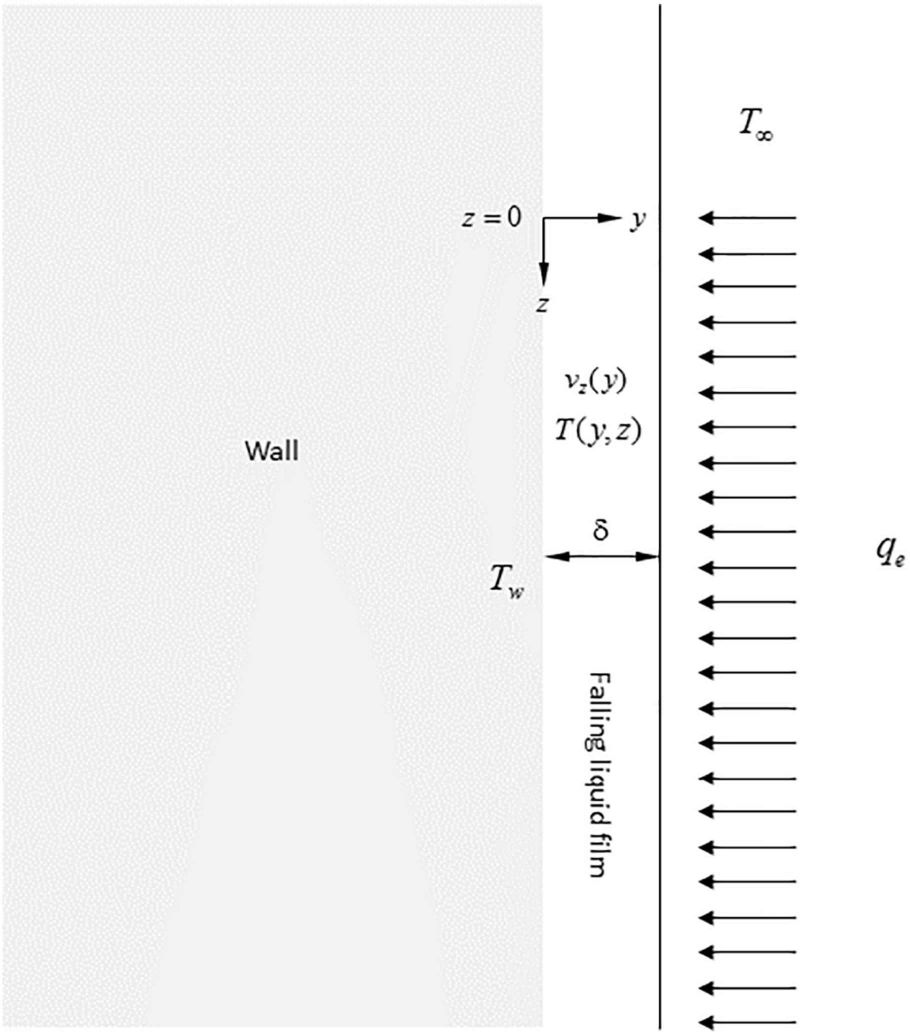

Fig. 1. Schematic representation of the heat transfer problem considered.

Table 1
Summary of the dimensionless parameters used in the simulations.

Figure	$\theta_{\zeta=0}$	$\theta_{\xi=0}$	$\theta_{\xi\to\infty}$	Q_e	Nu	Pe	τ
2(a); 3(a); 4(a); 5(a)	1	1	1	0.3	1	10	1
2(b)	1	1	1	0.3	1	10	0
3(b)	1	1	1	0.3	1	100	1
3(c)	1	1	1	0.3	1	0.1	1
4(b)	1	1	1	0.3	0	10	1
4(c)	1	1	1	0.3	0	10	0
5(b)	1	1	1	0.6	1	10	1

With

$$v_{z,\max} = \frac{\rho_L g \delta^2}{2\mu_L} \qquad v_{z,m} = \frac{\int_0^W \int_0^\delta v_z dydx}{\int_0^W \int_0^\delta dydx} = \frac{\rho_L g \delta^2}{3\mu_L} = \frac{2}{3} v_{z,\max} \tag{5}$$

In Eq. (5), $v_{z,\max}$ is the v_z at $y = \delta$ from Eq. (4).

The energy equation for the falling film can be written as