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On the optimum mass transfer of flat absorbing falling films

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ABSTRACT

The coupled heat- and mass-transfer of the absorbing falling film is considered in the flat-film approximation. We study the influence of the operating conditions on the absorption efficiency in a fully non-dimensional framework and find an optimal Reynolds number, which can be interpreted as an optimal film thickness. We also test various thermal wall boundary conditions to select the best approximation compared to a realistic test case.

1. Introduction

Absorbing wavy falling films represent a great challenge for the numerical modeling. Owing to the complexity introduced by the dynamic free-surface evolution almost all literature on falling films deals with the flat (Nusselt) film. An overview on the strategies in modeling of absorbing falling film can be found in Killion and Garimella [1]. They give a detailed review of the most important works and pay particular attention to the assumptions made by each individual publication. One of the most notable teams is gathered around Nakoryakov and Grigor'eva, who have contributed publications over a period of almost 35 years starting with Grigor'eva and Nakoryakov [2]. Some of the approximations introduced by them are still common practice. Grossman [3] further improved the existing model by replacing the uniform velocity with the parabolic velocity profile. He obtained approximate solutions for the temperature and concentration fields in form of a series expansion considering an adiabatic and an isothermal wall. Since that time the model has been extended by including film-thickness variations, a non-linear vapor–liquid equilibrium condition, shear stress at the free surface, the Eckert–Schneider relation, a non-isothermal wall, as well as an energy equation including interdiffusion and variable thermophysical properties. A detailed summary can be found in [1] in their Table 1.

Despite of the large amount of knowledge acquired, there is still improvement needed for the model. In particular, the film waviness triggered by an inherent instability [4] is still lacking in most of the investigations. The waviness leads to transversal convection and represents one of the key effects for the enhancement of the absorption efficiency. Several authors considered the wavy film absorption by modeling the interfacial deformation as a sinusoidal capillary wave or roll wave. The corresponding investigations are summarized in Table 4 of [1]. Another major factor effecting the absorption efficiency is the presence of non-absorbable gases as shown by Yang and Jou [5].

Recent numerical studies considering the flat film were carried out by Yoon et al. [6], Bo et al. [7] and Karami and Farhanieh [8,9]. The first and the second work are dealing with a fully dimensional formulation and treat the influence of several operating conditions and variable thermophysical properties, respectively, on the heat- and mass-transfer coefficients. The latter investigators included a transverse velocity component in the flat-film model and studied the dependence of the averaged Sherwood and Nusselt numbers on the Reynolds number and the inclination angle.

The motivation for the present work derives from some shortcomings of the previous investigations of the flat film. Firstly, this is the use of the Eckert–Schneider relation which has not been implemented, even in cases in which the assumptions would call for it. Therefore, we present a detailed derivation of the free surface-boundary conditions in Section 3.3 leading to the Eckert–Schneider relation. Secondly, we develop a fully non-dimensional formulation of the given problem in section 3.4. We then test several thermal wall boundary conditions to select the best approximation compared to a realistic configuration. Finally, we adjust the resulting parameters such that they represent meaningful operating conditions of a common LiBr–H_2O-device and present the influence of the operating conditions on device performance by varying the non-dimensional parameters identified.

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Nomenclature

x, y	streamwise, wall normal coordinate
θ	inclination angle
L^*	length of the plate
g_x	gravity in streamwise direction, $g_x = g\sin\theta$
δ^*_{Nu}	Nusselt film thickness, (1b)
Γ	total incoming mass flux per unit length in spanwise direction
T^*_0	inlet/reference temperature
P^*_0	system/reference pressure
C^*_0	reference concentration
T^*_{d}	dew point temperature of H_2O corresponding to P^*_0
γ	linear concentration coefficient, $\gamma = (\partial C^*/\partial T^*)_{P^*_0}$
C_{e}	equilibrium concentration at the free surface, (6)
ζ	deviation of the inlet concentration from equilibrium
C_{s}	inlet concentration of the solution, $C^*_{\mathrm{s}} = C^*_0 + \zeta^*$
T_{c}	inlet temperature of the coolant
$\boldsymbol{u}$	velocity field
T	temperature field of the liquid film
C	concentration field (refers to the absorbent)
Θ	temperature field of the coolant
$\overline{\Theta}$	averaged coolant temperature (mixing temperature), (19)
$\dot{m}$	mass flux density due to absorption
$\dot{M}$	total mass flux due to absorption
$\dot{M}_{\mathrm{rel}}$	relative total mass flux, $\dot{M}_{\mathrm{rel}} = \dot{M}/\mathrm{Re}$
$\dot{M}_x$	cumulated mass flux, $\dot{M}_x = \int_0^x \dot{m}(x')\,\mathrm{d}x'$
$\dot{q}$	heat flux density
$\dot{Q}$	total heat flux
η	dynamic viscosity
ρ	density
ν	kinematic viscosity, $\nu = \eta/\rho$
λ	thermal conductivity
c_p	(isobaric) heat capacity
κ	thermal diffusivity, $\kappa = \lambda/(\rho c_p)$
D	binary diffusion coefficient
h	(specific) enthalpy
Δh	heat of absorption, $\Delta h = h'' - h_{\mathrm{d}} - h$
ΔT^*	characteristic temperature difference, $\Delta T^* = T^*_0 - T^*_{\mathrm{c}}$
ΔC^*	characteristic concentration difference, $\Delta C^* = \gamma\Delta T^*$
$\Delta C', \overline{\Delta C'}$	local, averaged driving potential
$\alpha, \bar{\alpha}$	local, overall heat transfer coefficient
$\beta, \bar{\beta}$	local, overall mass transfer coefficient
H	height of the cooling channel, $H = 2h$

Non-dimensional parameters

Re	Reynolds number, (11)
Pr	Prandtl number, $\mathrm{Pr} = \nu/\kappa$
Pe	Péclet number, Pe = Re Pr
Le	Lewis number, $\mathrm{Le} = \kappa/\nu$
St	Stefan number, (14)
Ξ	scaled equilibrium concentration, (14)
ε	aspect ratio, $\varepsilon = \delta^*_{\mathrm{Nu}}/L^*$
ξ	apparatus parameter, (16)
Λ	ratio of the thermal conductivities $\Lambda = \lambda_c/\lambda$
$\mathrm{Nu}, \overline{\mathrm{Nu}}$	local, overall (wall) Nusselt number
$\mathrm{Sh}, \overline{\mathrm{Sh}}$	local, overall Sherwood number

Subscripts

s	solution
c	coolant
g	gaseous phase
0	reference point
d	dew point
Nu	Nusselt solution (film)
Po	Poiseuille flow (coolant)
G	values that refer to Grossman [3]

Superscripts

$*$	dimensional quantity
$'$	saturated liquid
$''$	saturated gas
$\bar{a}$	average of the quantity a

2. Geometry

We consider a typical setup of a falling-film device as sketched in Fig. 1. A binary mixture (absorbent + absorbate), called solution (subscript s) in the following, enters the system at $x^* = 0$ with inlet temperature T^*_0 and inlet mass fraction C^*_s. The mass fraction is called concentration throughout the paper. The asterisk indicates dimensional variables other than thermophysical properties or transfer coefficients. The solution flows over a plate inclined with respect to the horizontal by the angle θ. We assume a non-volatile absorbent, thus the ambient atmosphere consists of the (vaporized) absorbate only and the constant system pressure P^*_0 corresponds to the vapor pressure of the absorbate. The binary solution is cooled by a counter-current coolant flow (subscript c) entering the system at $x^* = L^*$ with the inlet temperature T^*_{c} leading to the coupled heat and mass flux $\dot{q}^*$ and $\dot{m}^*$, respectively, across the free surface. For a plate with an inclination angle θ one finds the flat-film solution, also referred to as Nusselt solution, for the velocity profile $\boldsymbol{u}^*_{\mathrm{Nu}}$ as function of the wall-normal coordinate y^* and for the film thickness δ^*_{Nu}

$$\boldsymbol{u}^*_{\mathrm{Nu}} = \frac{g_x}{\nu}\left(y^*\delta^*_{\mathrm{Nu}} - \frac{y^{*2}}{2}\right)\boldsymbol{e}_x, \tag{1a}$$

$$\delta^*_{\mathrm{Nu}} = \left(\frac{3\nu\Gamma^*}{\rho g_x}\right)^{1/3}, \tag{1b}$$

where we have used the acceleration of gravity in streamwise direction $g_x := g\sin\theta$, the kinematic viscosity of the solution ν, its density ρ and Γ^*, which is the mass flux of the solution per unit length in spanwise direction. The coolant mass flux is Γ^*_{c}. Eq. (1) are the solution of the steady-state streamwise momentum balance for an infinitely extended film $\nu\partial^*_{yy}u^* = -g_x$ with the boundary conditions $u^*|_{y^*=0} = 0$ (no slip at the plate) and $(\partial^*_y u^*)|_{y^*=\delta_{\mathrm{Nu}}} = 0$ (no shear stress at the free surface).

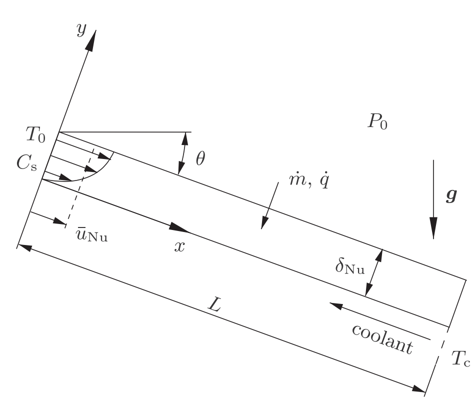

Fig. 1. Simplified model of an absorbing falling-film device. All quantities are dimensional (asterisks are omitted).