



A numerical model for combined heat and mass transfer in a laminar liquid falling film with simplified hydrodynamics



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ABSTRACT

We present a model describing simultaneous heat and mass transfer of an absorbing or desorbing laminar liquid film flowing over a vertical isothermal plate. We start with a formulation which is comparable to established models by using simplifying assumptions such as homogeneous velocity and constant film thickness. In contrast to those, we allow for effects like change in properties and differential heat of solution within the bulk of the film. Additionally, enthalpy transport due to interdiffusion is accounted for. The impact of the considered effects are discussed and compared.

The numerical solution is obtained by utilising a Newton–Raphson scheme to solve the finite difference formulation of the governing equations. Since the temperature gradients adjacent to wall and phase boundary are expected to be large, we discretise the equations on an irregular grid. The results of the model agree very well with established analytical models.

It is found that the influence of released differential heat of solution within the bulk is relatively small. However, the impact on the temperature distribution is in the same order of magnitude as the one of a change in properties. Moreover, when comparing desorption with absorption under equivalent conditions, the mass transfer rate during absorption is higher than during desorption.

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1. Introduction

Simultaneous heat and mass transfer occurs in nature as well as in various technical apparatuses. While in nature highly efficient systems (e.g. lungs or villi) have evolved, we still lack full understanding of the process. In energy engineering, efficient heat and mass transfer is crucial to obtain high performing thermodynamic cycles at low cost. Heat driven cycles, especially absorption chillers, rely mostly on transfer effectiveness and hence require diligent analysis and design.

An investigation of property and transfer issues with regard to irreversibilities as well as cycle restrictions has been provided earlier [1]. Herein, properties of working fluids and their thermodynamic behaviour are discussed but for heat and mass transfer only lumped parameters are used, which allows no real understanding of working fluid impact. Inside absorption chillers, falling film heat exchangers are widely-used as absorber, desorber, and evaporator. Therefore, modelling of falling films is significant for understanding cycle behaviour, design, and optimisation.

Although the properties vary with concentration and temperature, most authors assume them to be constant. Bo et al. [2] discuss this influence by comparing results with and without variable

property data and they report a reduction in mass transfer rate by 6.5% during absorption over a flow distance of 1 metre when variable properties are considered. In our work a similar comparison is enlarged upon occurring differential heat of solution within the film. Since most absorption chillers work with aqueous LiBr solution, the respective property data have been used for this article, however, for new or tailor-made working fluids, this assessment will be valuable also.

2. State of the art

One of the first models describing vapour absorption into a thin film was introduced by Nakoryakov and Grigor'eva in 1977 [3]. They assumed a uniform flow velocity throughout the film. In 1983, Grossman [4] extended the model by using a fully developed, laminar Nusselt solution as velocity profile. Since these pioneering works, heat, mass, and momentum transfer in falling films have been widely investigated. An extensive literature review up to 2001 has been provided by Killion and Garimella [5]. Recently, modelling of details such as surface tension effects, solitary waves, and mass transfer in the entrance have received considerable attention [6–10]. Solitary waves have been investigated by Islam et al. [7] using a finite difference method. They show that solitary waves produce recirculation zones in the film and conclude that these have significant effect on heat and mass transfer and thus

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Nomenclature

c_p	Heat capacity J/(kg K)
D	Mass diffusivity m^2/s
g	Gravitational acceleration m/s^2
h	Enthalpy J/kg
\bar{h}	Partial massive enthalpy J/kg
$Le = \lambda/(D \cdot c_p \cdot \rho)$	Lewis-Number –
\dot{m}	Mass flux $kg/(m^2 s)$
p	Pressure Pa
\dot{q}	Heat flux W/m^2
$St = (\Delta h_{sor}(\xi_{eq} - \xi_0))/(c_p(T_{eq} - T_0))$	–
T	Temperature K
u	Longitudinal velocity m/s
x	Longitudinal coordinate, streamwise m
y	Transversal coordinate m

Greek letters

$\dot{\Gamma}$	Mass flow per unit length $kg/(m s)$
$\gamma^+ = (\xi - \xi_0)/(\xi_{eq,0} - \xi_0)$	dimensionless mass fraction –
$\Delta \bar{h}, \Delta \bar{y}$	Abbreviations, please see Eq. (14)
Δh_{sor}	Heat of sorption J/kg
δ	Film thickness m

$\eta^+ = y/\delta$	dimensionless y -coordinate –
$\theta^+ = (T - T_0)/(T_{eq,0} - T_0)$	dimensionless temperature –
λ	Thermal conductivity $W/(m K)$
μ	Dynamic viscosity Pa s
ξ	Mass fraction kg/kg
$\xi^+ = (\lambda \cdot x)/(\rho \cdot c_p \cdot u \cdot \delta^2)$	dimensionless x -coordinate –
ρ	Density kg/m^3

Subscripts

0	Inlet condition
A	Absorbate e.g. water in liquid state
eq	Equilibrium
ϑ	Temperature in Celsius $^{\circ}C$
if	Interface
i	node index in longitudinal direction (x)
j	node index in transversal direction (y)
s	Solution of absorbent e.g. LiBr–H ₂ O
v	Vapour e.g. steam
w	Wall

enhance absorption rates. Moreover, the entrance region has been investigated analytically by Nakoryakov et al. [8]. They have obtained self-similar solutions for temperature and concentration in the film assuming a uniform velocity profile. Latest numerical calculations by Hofmann and Kuhlmann [11] suggest optimised Reynolds numbers, which have been interpreted as an optimal film thickness. In their work they closely investigate both the wall and the free surface boundary condition. Since a fully developed flow is assumed, they compare the obtained numerical solution to Grossman’s findings [4] and observe only minor deviations close to the inlet. Although few authors [2,12], include variable property data in their investigations, neither of these accounts for differential heat of solution occurring in the bulk of the flow. The release of differential heat of solution has been considered by van der Weken and Wassenaar [13]. However, in this study all fluid properties have been kept constant throughout the process.

3. Model description

The considered thin film is depicted in Fig. 1. In this work, we assume a film thickness δ corresponding to Nusselt’s solution $\delta = \sqrt{\frac{3\dot{\Gamma}\mu}{g\rho^2}}$, meaning the film thickness δ for a given specific flow rate $\dot{\Gamma}$ agrees with Nusselt but the profile does not. In other words, the usual ‘no slip’ condition at the wall is neglected and the average velocity has been used as flow velocity across the entire film. Thus, the averaged flow velocity results from $\bar{u} = \dot{\Gamma}/\delta\rho$. This severe simplification is made for two reasons: first, in order to strictly distinguish between thermodynamic and hydrodynamic effects. Although a fully laminar flow regime was more realistic, further hydrodynamic simplifications would remain in connection with an absorbing falling film. Since diffusion occurs in unidirectional manner, there is a transversal velocity even though the hydrodynamic flow is already fully developed. However, laminar flow conditions (Nusselt profile) do not allow for a transversal velocity component. Furthermore, the thickness of the film changes throughout the process since mass is absorbed at the interface. In the present study the component balance covers the convective flux in flow direction only (see Eq. 1). Consequently, the film thickness is kept constant to maintain a consistent set of equations. If a

change in film thickness was considered, advective transport in transversal direction would be induced which is currently not included in the governing equations. The second reason is that we want to compare the results to the established analytical solutions which use exactly the same simplifications (see below). However, a full treatment of hydrodynamics will be given in a consecutive paper.

Overall, the following assumptions have been made:

- (a) constant flow velocity u across the film,
- (b) constant film thickness δ ,
- (c) constant pressure p throughout the entire film,
- (d) transfer of heat across the free interface,
- (e) negligible change in temperature T caused by dissipation throughout the film,
- (f) negligible diffusion and heat conduction in flow direction as compared to convection,
- (g) negligible vapour pressure of the absorbent,
- (h) incompressible fluid,
- (i) steady state,

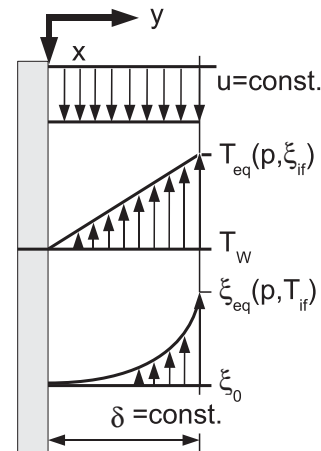


Fig. 1. Simplified distribution of longitudinal velocity u , temperature T , and mass fraction ξ in a laminar absorbing film.

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