International Journal of Thermal Sciences 126 (2018) 56–66

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Heat and mass transfer coefficients of falling-film absorption on a partially wetted horizontal tube

Niccolò Giannetti[a,*], Andrea Rocchetti[b], Seiichi Yamaguchi[a], Kiyoshi Saito[a]

[a] Department of Applied Mechanics and Aerospace Engineering, Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan
[b] Department of Industrial Engineering of Florence, University of Florence, Via Santa Marta 3, Firenze 50139, Italy

ABSTRACT

Detailed, reliable, and time-saving methods to predict the transfer characteristics of horizontal-tube falling-film absorbers are critical to control system operability, such that it is closer to its technical limitations, and to optimise increasingly complex configurations. In this context, analytical approaches continue to hold their fundamental importance. This study presents an analytical solution of the governing transport equations of film absorption around a partially wetted tube. A film stability criterion and a wettability model extend the validity range of the resulting solution and increase its accuracy. Temperature and mass fraction fields are analytically expressed as functions of Prandtl, Schmidt, and Reynolds numbers as well as tube dimensionless diameter and wetting ratio of the exchange surface. Inlet conditions are arbitrary. The Lewis number and a dimensionless heat of absorption affect the characteristic equation and the corresponding eigenvalues. Consequently, local and average transfer coefficients are estimated and discussed with reference to the main geometrical and operative parameters. Finally, a first comparison with the numerical solution of the problem and experimental data from previous literature is presented to support the simplifying assumptions, which are introduced and as a first model validation.

1. Introduction

It is not possible to consider heat transfer and mass transfer separately in several technical circumstances and physical processes. Absorption systems, such as chillers, heat amplifiers, and heat transformers, belong to the aforementioned category and represent an opportunity for clean and efficient energy conversion systems [1]. The main advantages of these systems include low-grade heat as the main energy source, higher reliability, and environmentally friendly refrigerants. This is accompanied by the possibility of realising a refrigerant pressure jump in a liquid phase. Accordingly, the compressor of a conventional system is substituted with a set of components, such as a solution pump, a generator, an absorber, and a solution heat exchanger, termed as a “thermal compressor” although the required exchange surface is significantly higher. In addition, extant studies indicated that the highest amount of irreversibility occurs in an absorber [2] and that global capacity and first law efficiency are limited by the amount of refrigerant that is absorbed [3,4]. Therefore, the intensification of the absorption process and proper design of an absorber are the critical factors that should be addressed. Horizontal-tube falling-film absorbers can realise high heat and mass transfer rates with compact size and negligible pressure losses. Conversely, the recent technical development of absorption chillers, heat pumps, and heat transformers corresponds to increasingly complex plant configurations [5,6], and specifically constitutes a step forward with respect to the theoretical background required for an accurate performance prediction, optimisation, and control. In general, the systems design approach continues to rely on empirical rules, heuristic correlations, or trial and error procedures on a global and component scale. The correlations rely on large sets of data, in which each set depends on experimental equipment as well as the specific boundary conditions of these measurements. Furthermore, devices that are designed to achieve high performance under nominal conditions may not exhibit a sufficient performance over most of the actual operative range. Similarly, in practice, conditions are transient and change continuously, because they are affected by interrelations with the external environment. Consequently, instantaneous conditions significantly differ from the design point. The construction of reliable and widely applicable theoretical models enables the design, optimisation, and definition of an effective control method without depending on trial and error procedures or empirical rules. Prior experimental studies on falling film absorption [7–12] report a limited amount of results with high

---

[*] Corresponding author.
E-mail address: niccolo@aoni.waseda.jp (N. Giannetti).

https://doi.org/10.1016/j.ijthermalsci.2017.12.020
Received 14 July 2017; Received in revised form 18 December 2017; Accepted 18 December 2017

Nomenclature

A, B	Eigenfunction coefficients
a, b	Power series coefficients
c_p	Isobaric specific heat, $J\cdot kg^{-1}K^{-1}$
D	Mass diffusivity, $m^2\cdot s^{-1}$
d	Diameter, m
E, H	Single variable exponential functions
F, G	Eigenfunctions
g	Gravity, $m\cdot s^{-2}$
h	Specific enthalpy, $kJ\cdot kg^{-1}$
htc	Heat transfer coefficient, $kW\cdot m^{-2}K^{-1}$
k	Thermal conductivity, $W\cdot m^{-1}K^{-1}$
l	Reference axial length, m
L_c	Characteristic length, m [$L_c = \nu^{2/3} g^{-1/3}$]
Le	Lewis number [$Le = \alpha\cdot D^{-1}$]
mtc	Mass transfer coefficient, $m\cdot s^{-1}$
Nu	Nusselt number [$Nu = htc\ L_c\cdot k^{-1}$]
P	Pressure, kPa
Pr	Prandtl number [$Pr = \nu\cdot\alpha^{-1}$]
Q	Heat flux, W
r	Outer tube radius, m
Re	Reynolds Number [$Re = 4\Gamma\cdot\mu^{-1}$]
S	Area, m^2
Sc	Schmidt Number [$Sc = \mu\cdot\rho^{-1}D^{-1}$]
Sh	Sherwood Number [$Sh = mtc\ L_c\cdot D^{-1}$]
t	Tube wall thickness, m
T	Temperature, K
u	Streamwise Velocity, $m\cdot s^{-1}$
v	Normal Velocity, $m\cdot s^{-1}$
W	Transversal extension of the wet part, m
WR	Wetting Ratio
x	Local tangential position, m
y	Local normal position, m

Greek symbols

α	Thermal diffusivity, $m^2\cdot s^{-1}$
β	Contact angle
ε	Dimensionless tangential position
γ	Dimensionless LiBr mass fraction distribution
η	Dimensionless normal position
Λ	Normalised heat of absorption [$\Lambda = h_{abs}(\omega_e-\omega_{in})\cdot\ (T_e-T_{in})^{-1}\ \omega_e^{\ -1} c_p^{\ -1}$]
λ,ϕ	Eigenvalues
θ	Dimensionless temperature distribution Γ Mass flow rate per unit length, $kg\cdot s^{-1}m^{-1}$
δ	Film thickness, m
μ	Dynamic viscosity, Pa·s
ρ	Density, $kg\cdot m^{-3}$
ω	LiBr mass fraction

Subscripts

0	Film breaking condition
abs	Absorption
av	Average
b	Bulk value
c	Cooling water side
e	Equilibrium
g	Global
i	Power series index
if	Interface
in	Inlet
max	Maximum
n, m	Eigenvalue/Eigenfunction indexes
o	Outlet
sat	Phases equilibrium
T	Temperature
v	Vapour
W	Wall

Superscripts

*	Dimensionless

uncertainties and within a relatively narrow range of operative conditions.

Reference [13] numerically discusses a model for film absorption and desorption of a laminar liquid film with constant thickness that flows over a vertical isothermal plate. A similar model was applied by Ref. [14] to a horizontal tube heat exchanger. References [15–18] introduce the effects of thickness and velocity distributions around a tube surface via numerical analyses. Finally, references [19–25] use the Volume of Fluid technique to examine and extract detailed descriptions of the wavy film dynamics, inter-tube droplets formation, detachment, and impact. Numerical analysis and computational fluid dynamics (CFD) are powerful tools that could be very precise when the problem is properly formulated. However, it is necessary to adequately consider the time required to reach an accurate solution and the fact that its validity is restricted to the specific case and the selected operative condition. Generalisable design guidelines are not directly provided by specific results as well as heuristic methods. Given this viewpoint, analytical approaches continue to maintain their fundamental importance to capture the physics of the problem and generalise the validity of the solution. The main limitations of extant analytical models include the geometry of the solid surface, assumptions of complete wetting, equilibrium of an inlet solution with vapour, uniform velocity profile, and film thickness [26–29]. Reference [28] indicated that uniform velocity profile and film thickness are responsible for approximately 20% deviations in the heat and mass transfer coefficient, and they under-predict approximately 40% of the distance required for the development of the thermal boundary layer. Therefore, this study successfully achieves an accurate and widely applicable analytical solution of governing equations of falling film absorption over a horizontal tube including the effects of thickness variations, incomplete wetting, and a corresponding reduction in transfer interfaces.

2. Physical model

The present analysis focuses on an absorptive liquid film flowing over a vertical row of horizontal smooth tubes. Droplet impact and hydrodynamic boundary layer development [19–25,30] are not discussed herein. Fig. 1 schematically illustrates the system under consideration. A single tube at uniform wall-temperature, T_w, is considered. A thin film of LiBr-H_2O solution impinges at the top ($x = 0$) and flows viscously down the tube due to gravity as a laminar incompressible liquid. Additionally, absorption can occur at the free-interface of the film based on the thermo-physical relation between the solution and the vapour. The enthalpy of vapour condensation that is released in the lithium-bromide/water mixture is rejected to the cooling water flowing inside the tube. Following the development of the thermal boundary layer, the temperature gradient related to the cooling process at the wall also influences the temperature at the interface, and this in turn establishes the equilibrium mass fraction at the vapour pressure within the heat exchanger and consequently controls mass transfer.