INTERNATIONAL JOURNAL OF REFRIGERATION 66 (2016) 93–104

Available online at www.sciencedirect.com

ScienceDirect

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

Laplace transform solution of conjugate heat and mass transfer in falling film absorption process

Mehdi Mortazavi, Saeed Moghaddam *

Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, FL 32603, USA

ARTICLE INFO

Article history:
Received 29 May 2015
Received in revised form 20 January 2016
Accepted 11 February 2016
Available online 18 February 2016

Keywords:
Absorption cooling/heating system
Falling film absorber
Lithium bromide
Laplace transform solutions

ABSTRACT

In this study, the conjugate heat and mass transfer process taking place during the absorption of a refrigerant vapor into a falling liquid film is analyzed using the Laplace transform method. The Laplace transform method has been previously utilized to model the process but under a uniform velocity profile assumption. Here, a more realistic linear velocity profile is employed. The results suggest that the uniform velocity profile assumption overestimates the refrigerant concentration across the liquid film, and underestimates the temperature profile and the vapor absorption rate. Overall, the uniform velocity profile assumption can result in up to 30% error in calculating the absorption rate. Using the new model, the effect of different flow parameters on the absorption rate has been studied. The efficacy of the model is demonstrated through comparison with various experimental and numerical results reported in the literature. The analytical solution developed in the present study provides a simple, fast and accurate approach for calculating the absorption rate at different operating conditions and fluid properties.

Solution de la transformée de Laplace du transfert de chaleur et de masse conjugué dans un processus d'absorption à film tombant

Mots clés : Système de refroidissement/chauffage à absorption ; Absorbeur à film tombant ; Bromure de lithium ; Solutions de la transformée de Laplace

---

* *Corresponding author.* Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, FL 32603, USA. Tel.: +1 352 392 0889; Fax: +1 443 538 6331.

E-mail address: saeedmog@ufl.edu (S. Moghaddam).

http://dx.doi.org/10.1016/j.ijrefrig.2016.02.013
0140-7007/Published by Elsevier Ltd.

Nomenclature

A_i	airy function
$B = (T_e - T_0)/(C_e - C_0)$	slope of saturation curve
B_i	airy function
C	refrigerant concentration [kg kg^{-1}]
c_P	heat capacity [J kg^{-1} K^{-1}]
$C_1, \ldots, C_4$	constants
D	diffusion coefficient [m^2 s^{-1}]
Δh_{abs}	heat of absorption [J kg^{-1}]
k_1, k_2	constants [K]
$Le = \alpha/D$	Lewis number
s	Laplace transform variable
$St = (c_P \cdot B)/(\Delta h_{abs})$	modified Stefan number
T	temperature [K]
u	longitudinal velocity [m s^{-1}]
$\bar{u}$	average velocity [m s^{-1}]
x	longitudinal coordinate [m]
y	transversal coordinate [m]

Greek letters

$\alpha = \lambda/(\rho \cdot c_p)$	thermal diffusivity [m^2 s^{-1}]
η	non-dimensional y-coordinate
ξ	non-dimensional x-coordinate
θ	non-dimensional temperature
γ	non-dimensional concentration
δ	solution film thickness [m]
λ	thermal conductivity [W m^{-1} K^{-1}]
ρ	density [kg m^{-3}]
Γ	flow rate [kg min^{-1} m^{-1}]

Subscripts

0	inlet condition
e	equilibrium
i	liquid-vapor interface
s	absorbent (LiBr solution)
w	cooling wall

1. Introduction

Absorption refrigeration systems (ARSs) are fundamentally attractive for our future energy economy because they can harness low quality heat energy for cooling. Their use is particularly attractive in combined heating, cooling, and power (CCHP) systems in which the ARS is powered by waste heat (Kim and Infante Ferreira, 2008; Saha et al., 2001). In the past several years, this field has seen an upsurge in research activities with the introduction of new heat exchanger configurations (Bigham et al., 2014a, 2014b; Cerezo et al., 2009; Nasr Isfahani and Moghaddam, 2013; Nasr Isfahani et al., 2013, 2014; Palacios et al., 2009; Warnakulasuriya and Worek, 2008) and ionic liquid (IL) absorbents (Dong et al., 2012; Kurnia et al., 2014; Zheng et al., 2014) that promise compact and robust systems. A better understanding of the transport processes involved in an absorption system is key to their development efforts. One of the fundamental processes taking place in an ARS is the absorption process that involves transport of refrigerant molecules into the absorbent solution in an exothermic process. The heat generated must be removed from the absorbent to perpetuate the absorption process. Understanding the transport phenomenon involved in the absorption process is essential in design of absorbers and performance evaluation of new refrigerant–absorbent pairs (Jeong and Garimella, 2002; Nasr Isfahani et al., 2013; Zheng et al., 2014).

The conjugate heat and mass transfer problem associated with the absorption process has been studied both analytically and numerically. Numerical simulations provide more accurate results, and are applicable to more complex geometries. Analytical solutions, on the other hand, are more efficient in terms of the computational efforts, and easier for design purposes. Nakoryakov and Grigoreva (Grigoryeva and Nakoryakov, 1977; Nakoryakov and Grigor'eva, 1977; Nakoryakov et al., 1997) presented the first analytical solution using the Fourier transform method and a set of simplifying assumptions. In their model, the interface is assumed to reach thermodynamic equilibrium instantly, as the flow enters the solution domain. Also, a linear relationship between the refrigerant concentration and temperature at different vapor pressures is assumed. Furthermore, the authors considered a uniform velocity profile instead of the actual parabolic velocity profile with the solution film and derived an analytical solution for an isothermal wall over which the absorbent flows. Grossman (1983) improved the Grigoryeva and Nakoryakov's (1977) model by using a parabolic velocity profile. However, solutions based on the Fourier method do not accommodate for inlet film conditions that differ from the solution domain boundary conditions (Nakoryakov and Grigoryeva, 2010). At the entrance region, oscillations occur in the solution due to disagreements between the inlet and the interface boundary conditions. Consequently, the Fourier solution is not applicable to the entire flow domain, and the entrance region needs to be treated separately. Nakoryakov et al. (2011) used a self-similar solution at the entrance region to avoid such difficulty, and Grossman (1983) used a numerical approach for the entrance region.

Recently, Meyer (2014) has introduced the Laplace transform method to solve the coupled partial differential equations for heat and mass transfer in laminar falling films. The flow velocity profile is assumed to be uniform. Adiabatic as well as isothermal walls are considered and compared. Unlike the Fourier method, the Laplace transform method is applicable over the entire flow length.

In the present study, the Laplace transform method is similarly applied to a laminar falling film flow but with a more realistic linear velocity profile. The model is then used to study the effect of operating conditions such as vapor pressure and solution flow rate on the absorption rate, and the results are compared with the available data in the literature.

2. Model

Fig. 1 depicts the flow domain composed of the absorbent (lithium bromide, LiBr) and refrigerant (water) solution flowing