Experimental Thermal and Fluid Science 68 (2015) 228–238

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Experimental assessment of vapour adiabatic absorption into solution droplets using a full cone nozzle

A. Zacarías [a], M. Venegas [b,*], A. Lecuona [b], R. Ventas [b], I. Carvajal [c]

[a] Instituto Politécnico Nacional, Academia de Térmicas/SEPI ESIME Azcapotzalco, Av. de las Granjas 682, Col. Santa Catarina, 02550 Distrito Federal México, Mexico
[b] Departamento de Ingeniería Térmica y de Fluidos, Universidad Carlos III de Madrid, Avda. Universidad 30, 28911 Leganés, Madrid, Spain
[c] Instituto Politécnico Nacional, SEPI-ESIMEZ-IPN, Edif. 5-3rd floor, UPALM, 07738 México, Mexico

ARTICLE INFO

Article history:
Received 12 November 2014
Received in revised form 1 April 2015
Accepted 2 May 2015
Available online 9 May 2015

Keywords:
Ammonia–lithium nitrate solution
Adiabatic absorption
Atomization
Full cone nozzle
Plate heat exchanger

ABSTRACT

This work investigates experimentally the adiabatic absorption of ammonia vapour into ammonia–lithium nitrate solution using a full cone nozzle and an upstream single-pass subcooler. Data are representative of the working conditions of adiabatic absorbers in absorption chillers. The nozzle was located at three different heights inside the absorption chamber, separated 0.165, 0.205 and 0.225 m from the bottom liquid surface. The diluted solution mass flow rate was modified between 0.04–0.08 kg/s and the solution inlet temperature between 23.5 and 30.6 °C. This paper analyzes the influence of these variables on the absorption ratio, mass transfer coefficient, outlet subcooling and approach to equilibrium factor. A linear relation between the inlet subcooling and the absorption ratio is observed. The approach to equilibrium factor for the conditions essayed is always between 0.64 and 0.87. Mass transfer coefficients and correlations for the approach to equilibrium factor and the Sherwood number are obtained. Results are compared with other ones reported in the literature.

1. Introduction

Absorption process in absorption cooling machines takes place when the refrigerant vapour coming from the evaporator is absorbed by the concentrated solution arriving from the generator, Herold and Radermacher [1]. This process is exothermic and the heat released should be extracted in order to increase the amount of vapour absorbed. Absorption can take place putting into contact solution and vapour in three different relations of geometrical continuity of phases: solution continuous-vapour continuous, solution continuous-vapour discontinuous and solution discontinuous-vapour continuous. Vapour absorption occurs in all cases through the liquid–vapour interface.

In the first case the solution is supplied as a continuous liquid sheet over the wall of a specific geometry and the vapour also in a continuous way co-currently or counter-currently with the liquid sheet, over its free surface. This is the conventional absorption method used in current commercial absorption machines using water and salts as working fluids, usually called falling film absorption. Absorption heat is evacuated through the wall.

In the second method vapour bubbles are injected into the solution (Infante Ferreira [2]), circulating co-currently or counter-currently throughout a specific channel. Channel walls allow evacuating the absorption heat. The last method consists of dispersing the solution inside a chamber filled with refrigerant vapour. Here the absorption heat is not evacuated from the chamber. The absorber is known as adiabatic, because heat is not extracted from the solution at the same time the mass transfer process occurs.

Adiabatic absorption taking place in the last method is an alternative to conventional designs of absorbers. It has received increasing attention in the last years by Ryan [3], Ryan et al. [4], Summerer et al. [5], Venegas et al. [6,7], Arzoz et al. [8], Warnakulasuriya and Worek [9,10], Palacios et al. [11,12], Acosta-Iborra et al. [13], Gutiérrez [14], Zacarías [15], Ventas [16], Zacarías et al. [17], Zacarías et al. [18], among others. In this configuration, the heat and mass transfer processes are separated into two different devices: the single-phase solution subcooler and the absorption chamber. In the subcooler, the solution is cooled below its saturation temperature at the current pressure and concentration, allowing absorption to only take place in the downstream adiabatic chamber. The claimed advantages of this technique are a more compact absorber and avoidance of the channelling, fingering effects and wetting difficulties of the absorber

* Corresponding author. Tel.: +34 916248776; fax: +34 916249430.
E-mail address: mvenegas@ing.uc3m.es (M. Venegas).

http://dx.doi.org/10.1016/j.expthermflusci.2015.05.001

Nomenclature

A	area (m^2)
Cp	specific heat at constant pressure ($kJ\,kg^{-1}\,K^{-1}$)
d_o	nozzle inner diameter (mm)
D	liquid mass diffusivity ($m^2\,s^{-1}$)
f	generic function
F	approach to equilibrium factor
G	mass flux, $G = \dot{m}/A$ ($kg\,m^{-2}\,s^{-1}$)
H	height of the absorption chamber (m)
h_m	mass transfer coefficient ($mm\,s^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	height from full cone nozzle to the bottom of the absorber (m)
L^*	non-dimensional height (L/H)
$\dot{m}$	total mass flow rate ($kg\,s^{-1}$)
P	pressure (Pa)
Pr_{cs}	solution Prandtl number ($Pr_{cs} = \mu_{cs}Cp_{cs}/k_{cs}$)
R_a	absorption ratio ($kg_v\,kg_{ds}^{-1}$)
Re_{cs}	solution Reynolds number ($Re_{cs} = 2\dot{m}_{cs}/\pi\mu_{cs}d_o$)
Sc_{cs}	solution Schmidt number ($Sc_{cs} = \mu_{cs}/\rho_{cs}D_{cs}$)
SD	standard deviation
Sh	solution Sherwood number ($Sh = h_m L/D_{cs}$)
T	temperature (°C)
V	volume (m^3)
We_{cs}	solution Weber number ($We_{cs} = (\dot{m}_{cs}/2)^2/\rho_{cs}d_o^3\sigma_{cs}$)
X	refrigerant mass fraction, or concentration (%)

Greek symbols

ΔH	Enthalpy difference (kJ)
ΔT	temperature difference, subcooling (°C)
ΔX	concentration difference (%)
ΔX_{lm}	logarithmic mean concentration difference (%)
α	thermal diffusivity ($m^{-2}\,s$)
μ	viscosity (Pa s)
ρ	density ($kg\,m^{-3}$)
σ	surface tension ($N\,m^{-1}$)

Subscripts

a	absorber, adiabatic
cs	concentrated solution
ds	diluted solution
exp	experimental
eq	equilibrium
i	inlet
o	outlet
v	vapour
w	water

Acronyms

DI	density indicator
EQI	energy and volumetric flow indicator
FPHE	fusion plate heat exchanger
LI	liquid level indicator
MVD	mean volume diameter (μm)
PI	pressure indicator
PIC	pressure control
PID	proportional integral derivative control
ΔPI	pressure drop indicator
QI	volumetric flow rate indicator
QIC	volumetric flow rate control
TI	temperature indicator
TIC	temperature control
WI	wattmeter

wall surface, problem that has been discussed by Jeong and Garimella [19] among others. In addition to this, a conventional single-phase heat exchanger can be used for the subcooler, in favour of volume and economy.

Dispersion of the solution inside the adiabatic chamber can be performed using different techniques, depending on the nozzle type used: flat fan, hollow cone, fog jet, full cone, etc. In the present work, a full cone is used to evaluate experimentally the absorption process, as its form factor is potentially compact. A review of this absorption method is performed below, including analytical, numerical and experimental studies.

1.1. Analytical studies

First-known analytical model of the simultaneous heat and mass transfer in independent drops was developed by Nakoryakov and Grigoreva [20]. This model is valid for static droplets and does not consider the angular variation of the concentration and temperature inside the spherical droplet. The authors presented an equation, valid to obtain the mass transfer coefficient, in terms of the Fourier (Fo), Lewis (Le) and Kutateladze (Ka) numbers.

A second analytical model was developed and validated experimentally by Fenton et al. [21], in this case for the absorption of ammonia vapour by a water spray. The model predicted the vapour absorbed to within 15% deviation when the ratio of water to ammonia is greater than or equal to that specified in ASHRAE directives [22]. In this case ammonia vapour removal from air is under interest because of safety and environmental protection purposes. Thus, the ammonia is much diluted into water.

Based on similar reasons, Huang [23] presented a model to calculate the removal efficiency of ammonia by a fine water spray. The author considers the effects of droplet pH, droplet diameter, ammonium concentration, ammonia concentration, and liquid-to-air ratio. The results showed that absorption increases as the droplet pH, ammonium concentration, or droplet diameter decrease and when the ammonia concentration or liquid-to-air ratio increase. The removal of ammonia from air is a more complex problem than the pure ammonia absorption as diffusion in the gaseous phase does not have to be taken into account in the later.

In a more recent paper, Su et al. [24] presented an improved analytical Newman droplet model [25] that can consider the absorption heat effect. Using this model, the absorption characteristics of the adiabatic spray into aqueous lithium bromide solution was studied. The results show that the absorption heat significantly affects the absorption process.

1.2. Numerical studies

One important limitation of analytical models is given by the simplifications assumed during the solution of the governing equations, which makes the models only valid for special cases. For this reason, and due to the lack of suitable experimental correlations in many occasions, several authors have solved in a numerical way cases that are more complex.

The first reported numerical models include those of Morioka et al. [26] and Lu et al. [27]. In both cases, the absorption of water vapour by water–lithium bromide solution spherical droplets is analysed when experiencing internal circulation, which is driven