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Experimental evaluation of ammonia adiabatic absorption into ammonia–lithium nitrate solution using a fog jet nozzle

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HIGHLIGHTS

- Adiabatic absorption of NH_3 vapour into NH_3–$LiNO_3$ using fog jet nozzle created spray.
- Pressure drop of the solution entering to the absorption chamber is evaluated.
- Approach to adiabatic equilibrium factor (F) is between 0.82 and 0.93 at 205 mm height.
- Experimental values of mass transfer coefficient and outlet subcooling are presented.
- Correlations for F and Sherwood number are given.

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ABSTRACT

This paper presents the experimental assessment of the adiabatic absorption of ammonia vapour into an ammonia–lithium nitrate solution using a fog jet nozzle. The ammonia mass fraction was kept constant at 46.08% and the absorber pressure was varied in the range 355–411 kPa. The nozzle was located at the top of the absorption chamber, at a height of 205 mm measured from the bottom surface. The diluted solution flow rate was modified between 0.04 and 0.08 kg s^{-1} and the solution inlet temperature in the range 25.9–30.2 °C. The influence of these variables on the approach to adiabatic equilibrium factor, outlet subcooling, absorption ratio and mass transfer coefficient is analysed. The approach to adiabatic equilibrium factor for the conditions essayed is always between 0.82 and 0.93. Pressure drop of the solution entering the absorption chamber is also evaluated. Correlations for the approach to adiabatic equilibrium factor and the Sherwood number are given.

1. Introduction

Mass transfer in the absorber is one of the main limiting factors for increasing performance and reducing size of absorption machines. Current technology use absorbers relying on laminar falling films, but other absorption methods have shown their potential for reducing both the heat and mass transfer area and, as a result, the absorber dimensions. One of these methods consists on dispersing the liquid solution in drops and/or free-flying sheets inside an adiabatic chamber, putting the solution in contact with the refrigerant vapour. This way, evacuating the absorption heat in the chamber is not possible.

This method has received growing interest in the last years, demonstrated in the review presented in what follows. In this configuration, the heat and mass transfer processes are separated in two devices: the single-phase solution subcooler and the adiabatic absorption chamber. The absorber is known as adiabatic because heat is not extracted from the solution at the same time the mass transfer occurs. The concentrated solution is cooled below the saturation temperature in the subcooler, allowing absorption to occur in the downstream adiabatic chamber, what increases the solution temperature. A conventional single-phase heat exchanger can be used for the subcooler, e.g. a commercial plate heat exchanger (PHE) in favour of cost and bulk. Other advantages of this method are a more compact absorber and avoidance of the wetting difficulties of the absorber tubes surface, problem that has been discussed by Jeong and Garimella [1], among others.

The mass transfer to solution drops and sheets and the internal heat transfer are processes of complex modelling as the mass and energy conservation equations must be solved simultaneously, taking into account fluid motion at both sides of the interface. To date, analytical models to predict the simultaneous variation of the

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Nomenclature

a	constant of the linear relation $X = a \cdot T + b$ at a given equilibrium pressure in the Dühring diagram, function of pressure, concentration and temperature (K^{-1})
A	area (m^2)
b	constant
Cp	specific heat at constant pressure (kJ kg^{-1} K^{-1})
d_o	nozzle exit diameter (mm)
D	liquid mass diffusivity (m^2 s^{-1})
D_h	hydraulic diameter (m)
DI	density indicator
EQI	energy and volumetric flow indicator
f	Darcy friction factor. Generic function
F	approach to equilibrium factor
Fo	Fourier number, $Fo = \alpha \cdot \tau / R^2$
PHE	plate heat exchanger
G	mass flux $G = \dot{m}/A$ (kg m^{-2} s^{-1})
h_m	mass transfer coefficient (mm s^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
Ka	Kutateladze number ($Ka = -a \cdot \Delta h / Cp_{cs}$)
L^*	characteristic length of the adiabatic chamber (m)
Le	Lewis number ($Le = \alpha_{cs}/D_{cs})_{eq}$ equivalent length (m)
LI	liquid level indicator
$\dot{m}$	mass flow rate (kg s^{-1})
MVD	mean volume diameter (μm)
P	pressure (Pa)
PI	pressure indicator
PIC	pressure control
Pr	Prandtl number ($Pr = \mu_{cs} \cdot Cp_{cs}/k_{cs}$)
QI	volumetric flow rate indicator
QIC	volumetric flow rate control
R	droplet radius (m)
R_a	absorption ratio (kg_v kg_{ds}^{-1})
Re	solution Reynolds number ($Re = 4\dot{m}_{cs}/\pi \cdot \mu_{cs} 7 d_o$)
Sc	solution Schmidt number ($Sc = \mu_{cs}/\rho_{cs} D_{cs}$)
SD	standard deviation
Sh	solution Sherwood number ($Sh = h_m L^*/D_{cs}$)
T	temperature (°C)
TI	temperature indicator
TIC	temperature control
u	solution average velocity inside the pipe or accessory (m s^{-1})
X	refrigerant mass fraction (%)
WI	wattmeter

Greek symbols

Δh	specific absorption heat (kJ kg^{-1})
ΔP	pressure drop (Pa)
ΔT	temperature difference, subcooling (°C)
ΔX	concentration difference (%)
ΔX_{lm}	logarithmic mean concentration difference (%)
ΔPI	pressure drop indicator
α	liquid thermal diffusivity (m^2 s^{-1})
μ	viscosity (Pa s)
ρ	density (kg m^{-3})
σ	surface tension (N m^{-1})
τ	time (s)

Subscripts

a	absorber
ad	adiabatic
cs	concentrated solution
ds	diluted solution
exp	experimental
eq	equilibrium
fric	frictional
i	inlet
o	outlet
v	vapour

concentration and temperature, considering size, velocity, internal circulation, flow pattern, etc. do not exist. If all these factors could be accurately considered, the characteristics of the heat and mass transfer in individual drops or sheets would correctly predict the global process that takes place in adiabatic absorbers of absorption refrigeration systems. To date, several studies analyse the simplified simultaneous heat and mass transfer in drops and sheets. Zacarías et al. [2] presented a revision of the works developed in relation to solution sheets. A review of the up to date efforts regarding absorption into solution drops is presented in the following:

1.1. Analytical studies

Nakoryakov and Grigoreva [3] developed the first-known analytical model of the simultaneous heat and mass transfer in independent spherical drops. 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 present an equation, valid to obtain the mass transfer coefficient, in terms of the Fourier (Fo), Lewis (Le) and Kutateladze (Ka) numbers.

Fenton et al. [4] developed, and validated experimentally, an analytical model 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 [5]. 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.

For similar reasons, Huang [6] 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 that the pure ammonia absorption as diffusion in the gaseous phase does not have to be taken into account in the later.

1.2. Numerical studies

The main limitation of analytical models is given by the simplifications assumed during the solution of 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 more complex cases in a numerical way.

Apparently the first reported numerical models include those of Morioka et al. [7] and Lu et al. [8]. In both cases, the absorption of water vapour by water-lithium bromide solution spherical droplets is analyzed when experiencing internal circulation, which is driven