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Experimental and numerical study of a falling film absorber in an ammonia-water absorption chiller

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ABSTRACT

In this paper, experimental and numerical studies of heat and mass transfer in a falling film absorber are presented. The investigated absorber is a plate heat exchanger used in a falling film configuration. The ammonia-water solution flows in a falling film mode along the plates. The vapour flows co-current with the falling film and the coolant fluid is in a counter-current flow with the falling film. A prototype of ammonia-water absorption chiller is used to experimentally study the absorber behaviour in real operating conditions. A macro study of the absorber and a local analysis deduced from local temperatures measurements along the falling film are presented. A numerical model and a simulation tool are developed in order to complete the experimental investigations. The associated numerical parametric study aims to separate the coolant mass flow rate impact. The model is validated with experimental data and a maximal relative error of 15% is observed between experimental and numerical results. The results of this study suggest that during the absorption process, mass transfers are controlled by the falling film mass transfer resistance and that the liquid-side heat transfer resistance is negligible.

1. Introduction

In the current context of air conditioning democratization, finding an alternative to vapour compression chillers is a major challenge for the future as it represents approximately 99% of the today's sold units and it has led to an important increase in electricity consumption and greenhouse gas emissions [1]. Ammonia-water absorption chillers are an alternative solution as they are thermally driven and generate cooling effect by using environment friendly refrigerant. These chillers are attractive both for solar air conditioning and for industry processes: they make possible the recovery of waste heat released by the industry (heat effluents, exhaust gases). Global demand for absorption chillers market is expected to increase in the next years [2]. However, this technology has to be improved to become competitive in terms of cost and operative behaviour.

Mittermaier and Ziegler [3] showed that the overall performance of absorption machines is mainly influenced by the absorber. Indeed, global performance of the chiller is impacted by low efficiency of the absorber heat and mass transfer process [4,5]. As a result, the absorber is one of the most critical components of the absorption chiller in terms of size, cost and efficiency: the understanding of its behaviour is fundamental to improve global performances of the chiller.

Many studies dealing with the absorption process in ammonia water absorption chillers have been performed with the aim of predicting and increasing heat and mass transfers in the absorber. Those phenomena are widely influenced by absorbers geometries and absorption methods.

The most common absorption methods are bubble absorption [6,7] and falling film absorption. The latter is recommended to improve heat and mass transfers even though thin liquid falling films which completely wet a solid surface are difficult to produce along some materials [8]. Most frequent geometries of absorbers are horizontal tube and vertical tube exchangers; they have been widely studied for different tube diameters [9–14]. But the miniaturization of absorbers is the target of a lot of studies, so the plate heat exchanger is another possible geometry, more compact, for falling film absorption [15–17].

Among performed research, many are either numerical or analytical. The authors established models for the falling film absorp-

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Nomenclature

A	transfer area [m^2]
Γ	mass flow per unit length [$kg \cdot m^{-1} \cdot s^{-1}$]
c	correction coefficient [–]
Cp	heat capacity [$J \cdot kg^{-1} \cdot K^{-1}$]
δ	thickness of the falling film [m]
dAi	interfacial area of the differential control volume [m^2]
ΔL	length of the differential control volume [m]
Exp	experimental
g	gravitational acceleration [$m \cdot s^{-2}$]
h	heat transfer coefficient [$W \cdot m^{-2} \cdot K^{-1}$]
H	specific Enthalpy [$J \cdot kg^{-1}$]
$\bar{H}$	partial enthalpy [$J \cdot kg^{-1}$]
K	mass transfer coefficient [$m \cdot s^{-1}$]
λ	thermal conductivity [$W \cdot m^{-1} \cdot K^{-1}$]
L	length of the absorber [m]
μ	dynamic viscosity [$kg \cdot m^{-1} \cdot s^{-1}$]
$\dot{m}$	mass flow rate [$kg \cdot s^{-1}$]
$\dot{m}_{NH3}$	mass flow rate of the ammonia absorbed or desorbed at the film/vapour interface [$kg \cdot m^{-2} \cdot s^{-1}$]
$\dot{m}_{H2O}$	mass flow rate of the water absorbed or desorbed at the film/vapour interface [$kg \cdot m^{-2} \cdot s^{-1}$]
η	mass effectiveness [–]
N_{NH3}	surface mass flow rate of the ammonia absorbed or desorbed at the film/vapour interface [$kg \cdot m^{-2} \cdot s^{-1}$]
N_{H2O}	surface mass flow rate of the water absorbed or desorbed at the interface [$kg \cdot m^{-2} \cdot s^{-1}$]
Np	number of plates
Num	numerical
P	pressure [Pa]
Q	heat flux [W]
ρ	density [$kg \cdot m^{-3}$]
T	temperature [K]
th	plate thickness [m]
U	global heat transfer coefficient [$W \cdot m^{-2} \cdot K^{-1}$]
x	mass fraction of ammonia in the liquid phase [–]
y	mass fraction of ammonia in the vapour phase [–]
z	mass fraction of ammonia in the absorbed or desorbed flow [–]

Subscripts

abs	absorber, absorbed, absorption
L	liquid
C	coolant fluid
cond	condenser
E	evaporator
film	falling film
G	generator
in	inlet
int	film/vapour interface
max	maximum
out	outlet
P	plate
rect	rectification exchanger
Ref	reference
SEN_L	sensible liquid
SEN_V	sensible vapour
SP	poor solution
SR	rich solution
sat	saturated solution
V	vapour
VC	condensate

tion [17–21]. For example, Goel and Goswami [15] analysed a counter current absorber using a finite difference method and empirical correlations for transfer coefficients to understand coupled transfers and Gommed et al. [22] used finite volume method to quantify the absorption process.

In a review article dedicated to numerical studies of falling film absorber, Killion and Garimella [23] mentioned that conclusions about the governing transfer resistances are often contentious and pointed out that for ammonia-water working fluid most of the authors neglect mass transfer resistances in vapour phase (considered as pure ammonia) or in liquid phase. In the present work, mass transfer resistances in both liquid and vapour phases are considered to discuss the absorption process.

Over the last few years, experimental studies have also been performed on the absorber in order to predict its behaviour and to determine the limiting transfer's occurrence. Among those, Kang et al. [16] experimentally investigated ammonia-water falling film absorption process. The authors compare the effect of various operating conditions on heat and mass transfer performances. Kwon and Jeong [24] experimentally studied the effect of the vapour flow direction on the absorption heat and mass transfer in a falling film helical coil absorber.

However, most studies are not performed in real operating conditions. Indeed, some test benches dedicated to the absorption process make possible the study of the absorber but the behaviour of the absorber is separated from the one of the global absorption chiller. Therefore, test conditions at the input of the absorber like pressure, vapour concentration and poor solution concentration, which are conditions dependent on all the elements of the machine, are not representative of real conditions at the input of the absorber in a real absorption chiller [6,24].

For example, in the work of Kang [16], the method enables operating conditions to vary but the absorber is tested in no representative conditions: the study occults the global chiller behaviour. Indeed, this study was conducted at a vapour concentration varying from 64.7% to 79.7% and a solution concentration varying from 5.0% to 15% while typical inlet concentrations are rather a vapour concentration of more than 98% (thanks to the rectification process) and a solution concentration varying from 25% to 50%.

At the opposite, Nagavarapu and Garimella [9] and Lee et al. [10] considered an absorber on a test facility replicating a functional absorption chiller and showed the importance of all the elements of the machine. Absorbers studied in these works are horizontal-tube falling-film absorbers which were especially designed for the study.

The purpose of the present study is to analyse heat and mass transfer in a plate heat exchanger used as falling film absorber, in order to predict its performances.

A prototype of ammonia-water absorption chiller was used to study the absorber behaviour in real operating conditions. This prototype with a cooling capacity of 5 kW was built in 2010 and numerous previous tests proved its ability to maintain steady-state conditions [25]. The concerned absorber is a commercial gasketed plate-and-frame heat exchanger used as falling film absorber. This technology was selected for its compactness and its low cost.

A global analysis at the input and output of the absorber and a local analysis thanks to temperature sensors inside the absorber are possible by means of the experimental device. But this experi-