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International Journal of Heat and Mass Transfer 51 (2008) 3362–3368

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Drop formation of swirl-jet nozzles with high viscous solution in vacuum-new absorbent in spray absorption refrigeration

F.S.K. Warnakulasuriya, W.M. Worek *

Department of Mechanical and Industrial Engineering, University of Illinois at Chicago, Chicago, IL 60607, USA

Received 15 September 2007; received in revised form 8 November 2007
Available online 15 February 2008

Abstract

In this paper, the drop formation properties of a lithium bromide salt solution Trane [Trane, Private communication, 1997, [1]], which is utilized in a new concept of spray absorber, is investigated. In the spray absorber of the absorption refrigeration cycles, the feasibility of forming droplets with an optimum diameter of 300 μm, calculated by the drop absorption model, were studied. To achieve above, a single nozzle spray chamber able to attain a low-pressure of 1.23 kPa (0.178 psia) pressure was built. The nozzles experimentally tested were swirl-jet nozzles. The differential pressure across the nozzles was varied from 50 to 200 kPa (7.25–29 psia). The flow rate in the experiment was varied between 0.018 and 0.043 kg/s (2.376–5.676 lb/min). The flow number that define the effective flow of the selected nozzles were 7.6×10^{-7}, 1.5×10^{-6} and 2.3×10^{-6} and the viscosity ratio of this disperse/continuous phase flow was 1300. The nozzles tested were able to produce drop sizes having a mean volumetric diameter (MVD) between 375 μm and 425 μm. Comparison of drop absorption model results to conventional absorber results shows a significant improvement in absorption.

Keywords: Absorption; Absorption chillers; Absorption models; Atomization; Sprays

1. Introduction

In multi-effect high performance absorption cycle chillers, the high temperature loops operate with highly concentrated salt solutions that are relatively viscous and corrosive. Consequently, the design of the corresponding apparatus, especially the absorber, presents engineering and material challenges. Currently, this system component is associated with an undesirable cost premium and reduction of effectiveness due to the size of the absorber.

The methodology that has been used in the absorber of conventional large commercial absorption chillers is falling-film heat exchangers. In an absorber, the rate which the refrigerant (i.e., water in a LiBr–H_2O system) in the form of vapor is absorbed by the concentrated salt solution is important. It has long been recognized that if this rate could be increased beyond that occurring in the falling film type of absorbers, this component could be reduced in size and its performance can be enhanced.

It is apparent that if the total absorption area of the salt solution could be increased, the rate of absorption of the water vapor by the salt solution would also increase. One obvious way of doing this is to introduce the absorption fluid in the form of the fine droplets, which could increase the rate of the absorption by an order of magnitude. It is known that the size of these droplets decreases, the total area exposed to the vapor increases, and the rate of absorption increases accordingly. Numerous studies by Benbrahim et al. [2], Morioka et al. [3], Ryan [4] and Flamensbeck et al. [5], have confirmed above effects demonstrating the improvement with experiments, analytical and numerical calculations. As shown in Fig. 1, a conventional absorber consists of a bundle of tubes covered with the absorbing solution which are surrounded by the water vapor to be absorbed. The rate of the absorption is directly proportional to the total tube area. If all the solution on these tubes can be converted into the drops with an average

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* Corresponding author. Tel.: +1 312 996 5610.
E-mail address: wworek@uic.edu (W.M. Worek).

0017-9310/$ - see front matter © 2007 Published by Elsevier Ltd.
doi:10.1016/j.ijheatmasstransfer.2007.11.015

Nomenclature

a, b, c, d	parametric constants
$\dot{m}$	mass flow rate
ΔP	differential pressure
ρ	density of solution
σ	surface tension
ν	kinematic viscosity

Subscript

L	liquid

of diameter of 300 μm, the total area would be increased by more than 200 times. Therefore, the rate of absorption could theoretically be increased by a similar factor. This spray absorption system is shown in Fig. 2. In the spray absorption system, the size of the absorber would be much smaller than that of the falling film absorber.

In this work, as a first step of investigation of the performance of the spray absorbers, the feasibility of creating the optimum drop sizes defined by the previously mentioned investigators Benbrahim et al. [2], Morioka et al. [3] and Ryan 1995 [4] and Flamensbeck et al. [5] with a new absorbent solution was studied. As a second step of investigation, analytical study to find the absorption rates of this process was performed and then compared it with conventional absorber performance. To find the absorption rates, “the Newmann model”, the best available model that represent the flow condition and absorbent properties in this experiment and drop formation results found from experiment, were used. Furthermore, conditions typically encountered in a commercial absorber were used. Based on previous studies De Corso [6], Wang and Lefebvre [7], Lefebvre [8] and Jones [9], the most appropriate atomization for the applications that handles high viscous solutions can be considered as the liquid sheet disintegration. Even with high viscous solutions, this form of atomization forms a conical liquid sheet, which gives higher flow rates and smaller droplets. This type of disintegration can be effectively achieved with pressure-swirl atomizers.

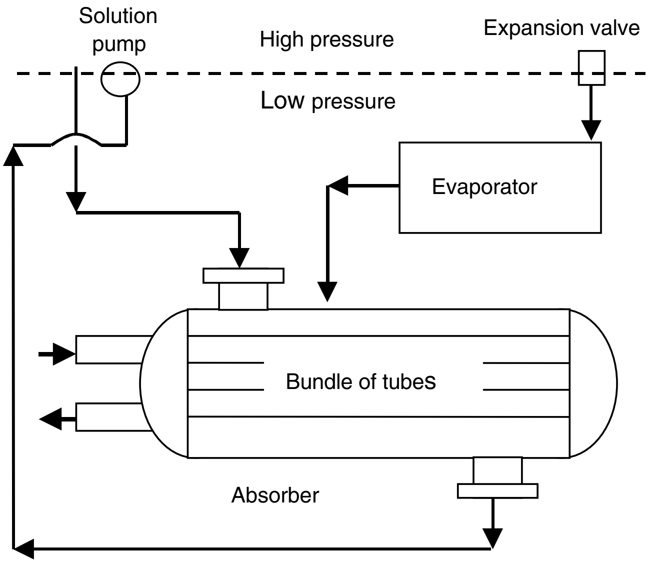

Fig. 1. Conventional absorber.

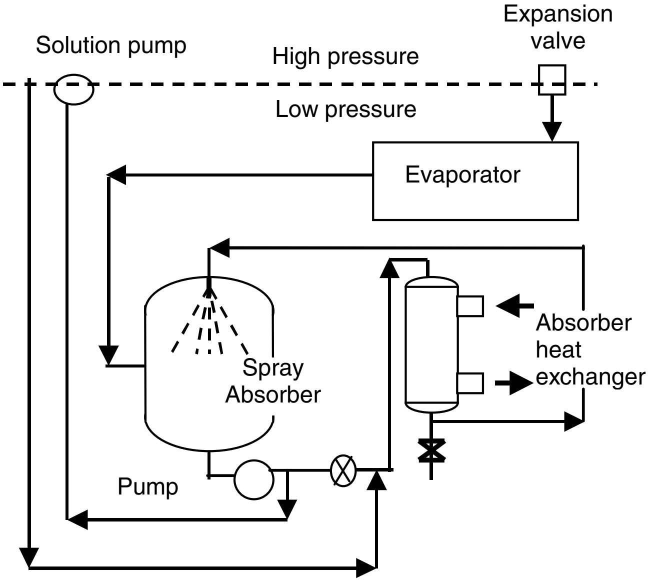

Fig. 2. Spray absorber with solution sub-cooler.

To generate the smallest possible droplet sizes keeping higher flow rates, when selecting pressure-swirl atomizing nozzles to conduct the experiments, recommendations given by all the above investigators, specifications given by the manufacturer and results obtained from the previous research carried out by authors for different kinds of pressure nozzles for similar operating conditions were used.

2. Drop formation theory

The development of the jet or sheet and the growth of the disturbances, which eventually leads to the disintegration into ligaments and drops, is the most effective method of atomization. There are several basic factors and processes associated with all methods of atomization, such as hydrodynamics of the flow within the atomizer, influence of aerodynamic forces in the surroundings, vital fluid properties such as viscosity and surface tension and turbulent liquid forces within the emerging liquid stream.

The parameters of importance for the spray investigated in this research are the resulting drop size, drop velocity,

Table 1
Ranges of operating parameters

Operating parameter	Required range
Required concentration of salt solution at nozzle	84%
Required nozzle pressure range	0–1.7 × 10^5 Pa (0–24.66 psi)
Required absorber pool temperature	92.2 °C (198 F)
Required solution temperature range at nozzle	65.5–82.2 °C (150–180 F)
Required absorber pressure	1.23 × 10^3 Pa (0.178 psi)

spray angle, number density and drop size distribution. The main effect on the absorption rate by the drops depends on the drop size, which maximizes the surface area for absorption. The factors that effect the changes in drop size are only considered in this work.

Mean drop size defines the quality of the fineness of the atomization process. Unfortunately, there are no equations that can be derived from first principles to directly find the mean drop size. The mean drop size considered in this work is the mean volumetric diameter (MVD), defined by

$$\mathrm{MVD} = D_{30} = \left[\frac{\int_0^\infty ND^3\mathrm{d}D}{\int_0^\infty N\mathrm{d}D}\right]^{\frac{1}{3}}. \tag{1}$$

As mentioned earlier, the main factors governing the atomization quality of pressure-swirl nozzles are liquid properties, the environmental condition surrounding the nozzle, the injection pressure and the size of the nozzle. The effective flow area (i.e., the size of the nozzle) of a pressure nozzle, usually described in terms of flow number (FN), is expressed as

$$\mathrm{FN} = \frac{\dot{m}_\mathrm{L}}{(\Delta P_\mathrm{L})^{0.5} \times \rho_\mathrm{L}^{0.5}}. \tag{2}$$

Due to the absence of an equation derived by first principles to define the dependency of the drop size on the above mentioned factors governing for atomization, the following empirical equation was used (i.e., Lefebvre [8])

$$\mathrm{SMD} \propto \sigma^a v^b \dot{m}_\mathrm{L}^c \Delta P_\mathrm{L}^d. \tag{3}$$

The mean diameter in the above equation is the Sauter mean diameter (SMD), however some other references (i.e., Jones [9]) have also used the above equation to correlate the MVD.

As was discussed, this work uses a new solution for absorbent and the real commercial absorber condition as specified in Table 1. The main objective of this work is to define the dependency of the drop size on the properties of the solution, the environment pressure and pressure difference across the nozzle, and the size of the nozzle.

3. Drop absorption theory

In the spray absorber, if the solution is at equilibrium, the vapor pressure is lower than the water vapor pressure, the solution is sub-cooled, and it will absorb water vapor. During the absorption process, the solution will become dilute and due to the heat evolved, the temperature will increase until the equilibrium pressure has increased to the absorber pressure. After this point, no further absorption will occur. The main factors that affect the water absorption into sub-cooled solution droplets are the level of sub-cooling, the chemical diffusivity, the droplet resident time, the internal fluid motion within the droplet (i.e., the Marangoni effect) and the capillary pressure.

In first principle theoretical models of the falling drop absorption, the species conservation equation is

$$\frac{\partial X}{\partial t} = K_\mathrm{D}\nabla^2(X). \tag{4}$$

This equation can be expanded adding convective terms in spherical coordinates for the surface composition of particles undergoing unsteady mass transfer with negligible external resistance. Therefore, the Eq. (4) becomes

$$\frac{\partial X}{\partial t} + u_r\frac{\partial X}{\partial r} + \frac{u_\theta}{r}\left(\frac{\partial X}{\partial \theta}\right) = \frac{K_\mathrm{D}}{r^2}\left[\frac{\partial}{\partial r}\left(r^2\frac{\partial X}{\partial r}\right)\right] + \frac{1}{\sin\theta}\left[\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial X}{\partial\theta}\right)\right], \tag{5}$$

where the vertical tangential direction variable is negligible, since the tangential velocity component is negligible. The most general boundary condition for this type of flow model is

$$X = X_i \text{ at } r = a. \tag{6}$$

This boundary condition assumes that the interface immediately reaches the equilibrium condition, X_i, which is ultimately experienced by the entire drop. The second boundary condition is

$$\frac{\partial X}{\partial r} = 0 \text{ at } r = 0. \tag{7}$$

The initial condition is simply specified as

$$X = X_0 \quad \text{at } t = 0 \text{ at any } r. \tag{8}$$

The sprays investigated in this work were largely non-oscillating and have low Peclet numbers (Warnakulasuriya [10]). Therefore, the oscillation and internal turbulence are not important factors. Based on the above observation, only the "Newman" model found appropriate from available models, for this flow conditions.

4. Newman model

When mass diffuses into a fluid particle, the concentration within the particle changes with time. The concentration fields for both internal and external fluids are related to the interface. If there is no chemical reaction at the interface, the species mass fluxes on each side are equal. If the Peclet number of a drop flow is small (i.e., $Pe \cong Pe_\mathrm{s} \cong 0$), the external resistance is negligible and hence, internal motion of the fluid within the drop can be ignored. Therefore, the concentration profiles display angular symmetry.

Further, the Sherwood number, Sh_P, the dimensionless concentration gradient at the drop surface, is a function only of diffusivity and the dimensionless time number. With these bases for the Newman absorption model [11], it is possible to simplify the species conservation Eq. (5), considering $u_r = u_\theta = 0$ gives:

$$\frac{\partial X}{\partial \tau} = \frac{K_D}{r^2}\left[\frac{\partial}{\partial r}\left(r^2\frac{\partial X}{\partial r}\right)\right] = \frac{K_D}{r}\left[\frac{\partial^2}{\partial r^2}(rX)\right]. \tag{9}$$

Eq. (9) was solved by Newman, with boundary and initial conditions as in Eqs. (6)–(8), to a series solution as

$$Sh_P = \frac{2\pi^2}{3}\sum_{n=1}^{\infty}\exp(-n^2\pi^2\tau)\Bigg/\sum_{n=1}^{\infty}\frac{1}{n^2}\exp(-n^2\pi^2\tau). \tag{10}$$

5. Experiment

The design and construction of the experimental setup was intended to obtain both drop formation data and drop absorption data. However, in this paper, the drop formation information is presented.

The experimental setup developed for this experiment was intended to produce a reproducible spray using experimental nozzles manufactured by spraying system incorporated, and provide good visibility of the spray process for observation and laser measurement of drop sizes and speeds as can be seen in Fig. 3.

Based on the spray of water at nozzle pressure of 6.89×10^4 Pa (9.98 psig) in atmospheric condition, the manufacturer's specifications of the nozzles tested are given in Table 2. Due to the high viscous nature of the absorbent salt solution and the low-pressure environment, dramatic changes in nozzle performance can be expected when running solution in the test system.

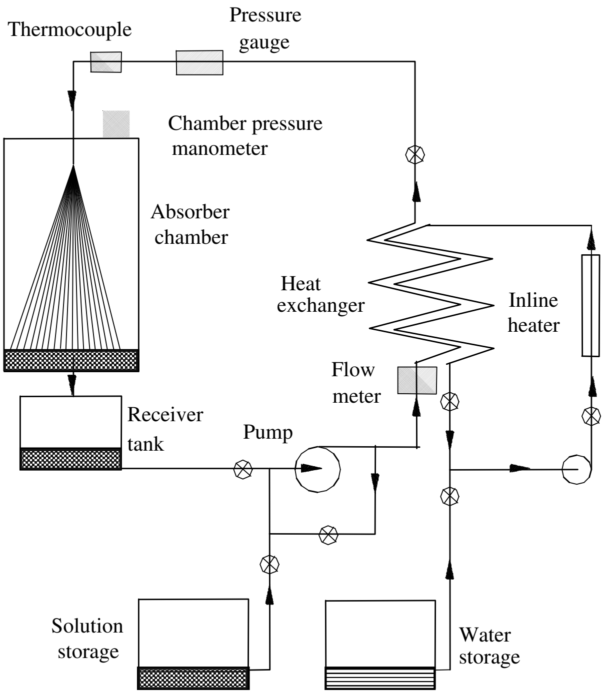

Fig. 3. Schematic of experimental test setup.

Table 2
Nozzle specifications

Model (swirl-jet)	Orifice diameter mm (in.)	Spray angle	Droplet size (MVD) μm	Flow number (FN)
1/8 BX SS 1 (SJ1)	1.6 (0.063)	52°	252	7.6×10^{-7}
1/8 BX SS 2 (SJ2)	1.98 (0.078)	52°	263	1.5×10^{-6}
1/8 BX SS 3 (SJ3)	2.39 (0.094)	52°	268	2.3×10^{-6}

To create and maintain the exact pressure condition, in accordance with the commercial absorbers inside the absorber chamber, the components in the high vacuum system consisted of two 20 L/min vacuum pumps. This system held the vacuum level of 25 Pa (3.63×10^{-2} psia) with the leakage rate of 4.67×10^{-6} scc/s.

For the drop size and velocity measurements, an aerometric phase doppler particle analyzer (PDPA) was used. This instrument is capable of measuring both drop size and velocity simultaneously.

6. Uncertainty analysis

The uncertainties associated with the results of this experiment are primarily caused by instrumentation and operating error. The instrumentation error, which is due to the accuracy, repeatability and calibration of instruments, affected the experimental results. The operating error caused by the variation of parameters such as properties of the solution and the operating conditions also introduced error into the experimental results.

The error analysis used the root mean square method of the form

$$\text{RMS error} = \sqrt{\sum\left[\Delta\left(\frac{\partial\rho}{\partial.\Delta}\right)\right]^2} \tag{11}$$

Table 3
RMS total of error limits on experimental results

Error source	Error	Percentage effect on the results		
		SJ1 (±)	SJ2 (±)	SJ3 (±)
Instrument error				
Nozzle temperature	0.25 °C (0.45 F)	1.2	0.9	0.8
Nozzle pressure	0.25%	1.3	0.75	0.5
Chamber pressure	0.1 mbar	1.35	0.8	0.65
Solution flow rate	0.2% flow	1.75	1.25	0.9
Operating error				
Solution concentration	0.1%	2.3	1.6	1.2
Solution density	0.2%	2.5	1.8	1.6
Solution viscosity	0.3%	2.4	2.1	1.7
RMS total of all errors		2.4	1.9	1.5

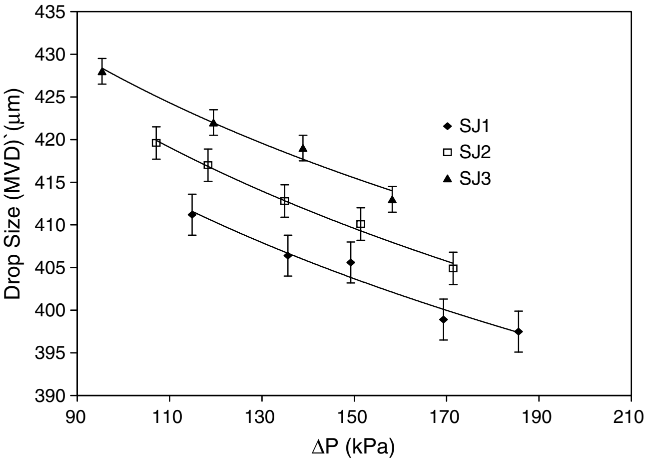

Fig. 4. Drop size information at 65 °C nozzle temperature.

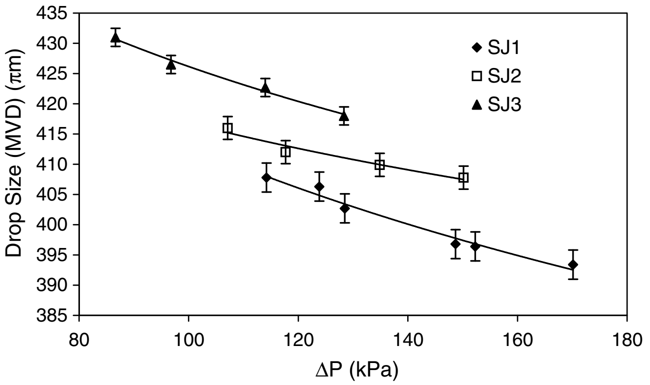

Fig. 5. Drop size information at 69 °C nozzle temperature.

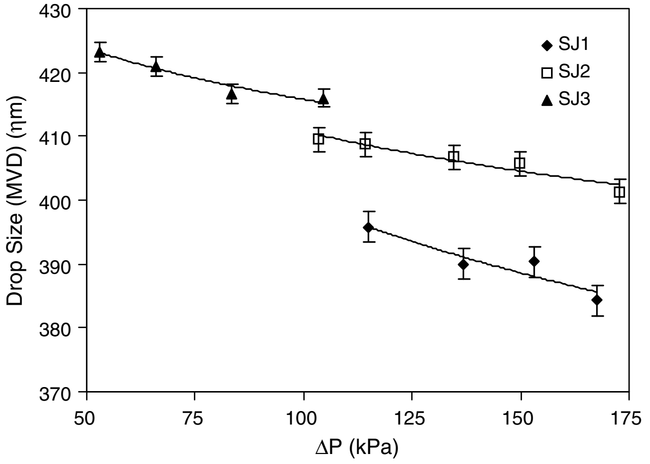

Fig. 6. Drop size information at 71 °C nozzle temperature.

The RMS errors calculated on experimental results of the drop size related to each nozzle tested are given in Table 3 and error bars based on the error limits are indicated on the results shown in Figs. 4–8.

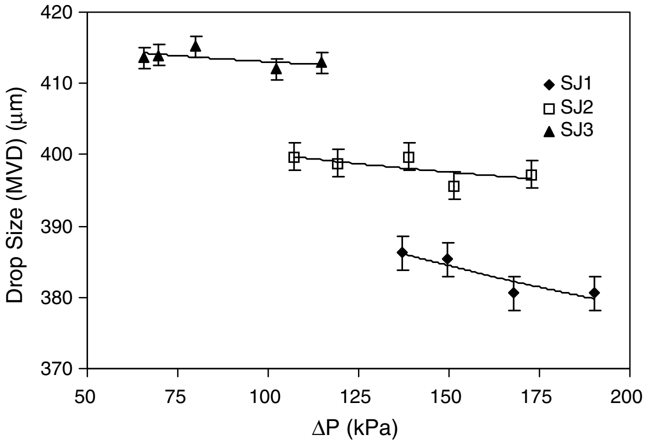

Fig. 7. Drop size information at 74 °C nozzle temperature.

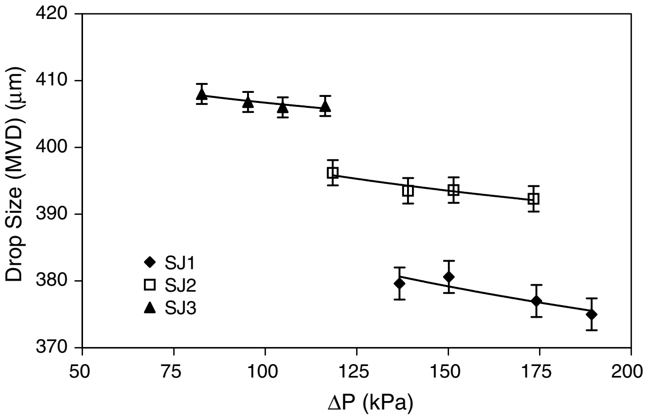

Fig. 8. Drop size information at 77 °C nozzle temperature.

7. Results and discussion

From the experimental results obtained for the nozzle flows under fully-developed and controlled-flow conditions, for each nozzle tested with new solution, the ranges of performance are given in Table 4.

The resulting plots, shown in Figs. 4–8, are based on different nozzle temperatures, different nozzle pressures and the different flow numbers (different nozzle sizes of swirl-jet nozzle). Even though the temperature represents the variation of density, viscosity and surface tension, the main effect of that is on the viscosity as can be seen in the comparison below:

Variation of density for 12 °C = 7.0 kg/m^3 (0.434 lbm/ft^2)
Variation of viscosity for 12 °C = 0.0033 kg/m s (7.97 lbm/ft h)
Variation of surface tension for 12 °C = 0.7 dynes/cm

Therefore, based on above observation, the temperature variation mainly affects the viscosity, and its effects on drop quality can be large. It can be seen that, the droplet size of

Table 4
Nozzle performance with "new absorbent" salt solution

Nozzle	Pressure range gauge, kPa, (psi)	Flow rate range, kg/s (lbm/min)	Mean velocity range, m/s (ft/s)	Drop diameter range (μm)
1/8 BX SS 1 (SJ1)	14.8–90 (2.15–13)	0.018–0.025 (0252.38–3.3)	29.03–38.5 (8.85–11.74)	373–411
1/8 BX SS 2 (SJ2)	0.5–10.6 (3.5–73)	3.56–4.488 (0.027–0.034)	32.18–41.07 (9.81–12.52)	387–420
1/8 BX SS 3 (SJ3)	(6.85)–2.38 ((47.2)–16.4)	3.96–5.676 (0.030–0.043)	32.31–42.41 (9.85–12.93)	384–423

a salt solution spray at a vacuum condition was as much as 150% larger as compared with water operating at atmospheric pressure. As the nozzle flows were maintained at fully developed conditions related to each nozzle, the plots were extrapolated to match and compare with the other nozzle performances. The value obtained for the coefficient *b*, the exponential that quantifies the effect of viscosity on drop diameter, in this experiment is around 0.25, which is much higher than the values in published data. This is due to the effect of viscosity is different in a low-pressure environment. Therefore, in this case, viscosity makes the adverse effect to the drop quality, than predicted by the literature (see De Corso [6], Wang and Lefebvre [7], Lefebvre [8] and Jones [9]). However, the above Figures also indicate that the dependence of drop quality on viscosity diminishes with increasing flow number (i.e., use of bigger nozzle).

The results clearly show that the increase of flow number degrades the spray quality, especially related to drop size. However, at the high-pressure differences, this effect is diminishes and becoming negligible.

From the results obtained by performing analytical calculation using Newmann's model, the Sherwood number has found and plotted against the Fourier number (dimensionless time number) as shown in Fig. 9. This plot is for drops with 400-μm drop diameter. The line marked "Conventional Absorber" in this figure is for typical 400 μm thick adiabatic laminar falling film occurring in the conventional absorber based on the tests conducted by Grossman [12]. The comparison of plots show the Sherwood number for drops can be far higher than that for the laminar falling-film.

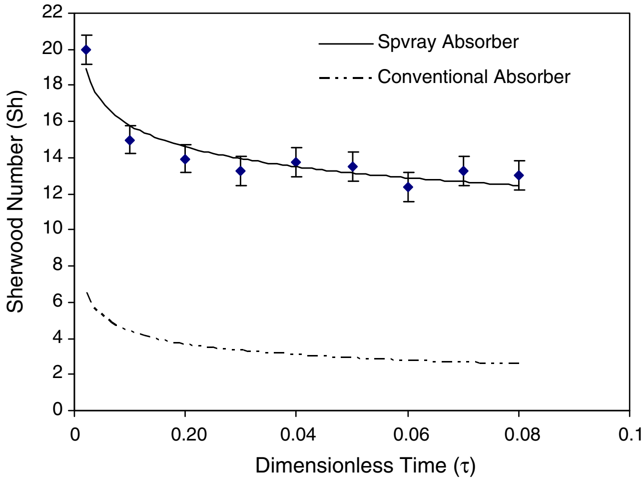

Fig. 9. Comparison of absorption results of conventional absorber and drop absorber.

8. Conclusions

In this experiment, the flow rate of the nozzle is directly related with the nozzle pressure. Therefore, any change in nozzle pressure directly affects the flow rate and the nozzle performance. Increasing the pressure differential across the nozzle decreases the drop sizes and hence increases the drop quality due to the increase of drop velocity with higher discharge pressures. As the drop velocity is one of the main factors to be considered in order to increase the drop absorption (lower velocity results in higher resident time allow more absorption), higher velocities will lower the absorption rate.

Despite of above discussed effects, the generation of droplets within the predefined acceptable drop size range under the specified absorber condition is feasible for high-viscous solutions with tested nozzles. As the experimental results indicate, the main effect of increasing the viscosity of the solution was not on the droplet size but on the spray angle.

Nozzles which were able to create higher swirl with high angular velocity flows give smaller drop size despite of running with solution having high viscosity and high surface tensions. Since the spray angle is a dependent of the viscosity of the solution, the high viscosity solutions will reduce the angle of the spray increasing the drop speed. However, as it is difficult to define a direct relationship between drop size and the drop speed, defining the dependency of drop size on above effects is highly impossible.

According to the comparison of absorption results for drop that takes place in the proposed spray absorber based on absorption model and the free falling results that take place in the conventional absorber, it can be clearly see that the spray absorber perform better.

References

[1] Trane, Private communication, 1997.

[2] A. Benbrahim, M. Prevost, R. Bugarel, Performance of a composite absorber, spraying and falling film, in: Proceedings of the International Workshop on Research Activities on Advanced Heat Pumps, Institute of Chemical Engineering, Graz, Austria, October, 1986.

[3] I. Morioka, M. Kiyota, A. Ousaka, T. Kobayashi, Analysis of steam absorption by a sub-cooled droplet of aqueous solution of LiBr, JSME Int. J. Ser. II 35 (1992) 458–464.

[4] W. Ryan, Water Absorption in an Adiabatic Spray of Aqueous Lithium Bromide Solution, Ph.D. thesis, Illinois Institute of Technology, Chicago, IL, 1995.

[5] M. Flamensbeck, F. Summerer, P. Riesch, F. Ziegler, G. Alefeld, A cost effective absorption chillder with plate heat exchanger using water and hydroxides, Appl. Therm. Eng. 18 (1998) 413–425.

[6] S.M. DeCorso, Effect of ambient and fuel pressure on spray drop size, ASME J. Eng. Power 82 (1960) 10.

[7] X.F. Wang, A.H. Lefebvre, Mean drop sizes from pressure-swirl nozzles, AIAA J. Propul. Power 1 (3) (1985) 200–204.

[8] A.H. Lefebvre, Atomization and Sprays, Hemisphere Publishing Corporation, New York, 1989.

[9] A.R. Jones, Design optimization of a large pressure-jet atomizer for power plant, in: Proceedings of the Second International Conference on Liquid Atomization and Sprays, Madison, WI, 1992, pp. 181–185.

[10] F.S.K. Warnakulasuriya, Spray Absorption Application for Multi-effect Absorption Cycles, M.S. thesis, University of Illinois at Chicago, Chicago, IL, 1998.

[11] A.B. Newman, The drying of porous solids, diffusion and surface emission equations, A.I.Ch.E. J. 27 (1931) 203–220.

[12] G. Grossman, Simultaneous heat and mass transfer in film absorption under laminar flow, Int. J. Heat Mass Transfer 10 (1982) 1785–1792.