Purdue University
Purdue e-Pubs

International Refrigeration and Air Conditioning Conference

School of Mechanical Engineering

2016

CFD Heat and Mass Transfer Studies in a R134a-DMF Bubble Absorber with Swirl Flow Entry of R134a Vapour

Santosh Kumar Panda
Indian Institute Of Technology Madras, India, santumech83@gmail.com

Annamalai Mani
Indian Institute Of Technology Madras, India, mania@iitm.ac.in

CFD heat and mass transfer studies in a R134a-DMF bubble absorber with swirl flow entry of R134a vapour

Santosh Kumar Panda, A. Mani*
Refrigeration and Air-conditioning Laboratory,
Mechanical Department, Indian Institute of Technology Madras, Chennai, INDIA.
Tel.: +91 44 22574666; E-mail address: mania@iitm.ac.in
* Corresponding Author

Abstract:

Study of absorber for heat and mass transfer analysis is essential to improve the performance of Vapour absorption refrigeration system (VARS). Tangential injection of refrigerant gas into liquid solution in a bubble absorber increases the heat and mass transfer characteristics by following rotary and translation path. In this study, a vertical absorber is considered for heat and mass transfer studies with refrigerant, R134a (1,1,1,2 – Tetrafluoroethane) and absorbent, DMF(dimethyl formamide). R134a vapour is injected into the absorber using two injectors of 4.8 mm inner diameter at an injection angle of 30° to the vertical axis and parallel to the azimuthal axis of the absorber which enhances mixing of R134a with liquid to increase the heat and mass transfer. Heat and mass transfer characteristic are presented in this paper in terms of operational parameters. Effect of solution pressure, solution flow rate, gas mass flow rate on heat and mass transfer rate, absorption rate, absorption efficiency, heat and mass transfer coefficients are computed numerical results.

1.Introduction

Absorber is one of the important components in vapour absorption refrigeration system. In an absorber, low temperature and low pressure refrigerant vapour from evaporator enters the absorber and is absorbed by weak solution. Heat of absorption is rejected to an external heat sink and weak refrigerant solution converted to strong solution. This work is being carried out on studies of absorber with swirl flow. Hence, it is proposed to study the absorber with swirl to improve its performance thereby improving the performance of vapour absorption systems. In applications such as absorption, distillation, the interaction of two phases occurs through injection of gas into the liquid pool and the equipment is designed based on the knowledge derived from the studies of the hydrodynamic parameters suitable for desired performance. Different fluid combinations viz. air-water, glycerol-air, methanol-air, ethanol-air, etc. have been used for bubble dynamics studies and ammonia–water, water-lithium bromide, R134a-DMF, etc. for absorber studies.

Many configurations or methods have been considered for increasing the rate of heat transfer in forced convection to reduce the size of the heat exchanger results in cost saving. Tangential entry of the fluid into an absorber can be achieved by single tangential inlet (circular or rectangular cross-section at different angles to the pipe axis) or more than one tangential entry, tangential inlet nozzles, tangential machined slots and tangentially drilled slots. Generally, tangential entry swirl generators have been used as a combination of axial plus tangential entry. With these types of swirler, the degree of swirl can be controlled by adjusting the proportion of fluid admitted by the axial and tangential fluid inlets.

Experimental studies conducted by Guo and Dhir (1994) for vertical tube with 6 injectors tangentially injected to find the velocity and temperature profile along the flow, heat transfer and swirl decay also calculated in turbulent regions along the flow. High axial velocity near the wall increases wall heat flux and high turbulence level for increase the heat transfer enhancement. A numerical modelling proposed by Lelea (1991) for micro-heat sink with tangential impingement jet of micro-tube used as injector to find the heat transfer and fluid flow analysis for different geometry by changing the diameter of injectors. Chang and Dhir (1995) conducted experiment on a vertical flow with tangential injection on single and two phase region for heat transfer on swirl flow to enhance the heat transfer performance.

An analytical study of the heat transfer characteristics was done by Algifri (1985) in order to studing decaying turbulent swirl flow generated by short twisted-tapes placed at the entrance of the test section for enhancement in the performance by solving Navier-Stokes equations with swirl flow. A propeller type swirl generator was developed, and its effects on heat transfer and fluid flow were investigated numerically and experimentally for air flow in a pipe. The effects of swirl flow on the heat transfer and pressure drop was studied by Bali (1998). It was observed that heat transfer increase at the cost of increased pressure drop. Salimpour and Yarmohammadi (2012) done experiment study with twisted tape inserted during convective condensation of R404A in a double counter-flow horizontal tube for enhancing heat transfer.

Martemianov and Okulov, proposed theoretical model for heat transfer (2003) and mass transfer (2002) in a axisymmetric swirl pipe flow for enhancement. Author's concluded vortex symmetry and vorticity distribution in the vortex core enhances the heat and mass transfer rate. Reynolds number and swirl number also plays major contribution on the enhancement. Study of local mass transfer behavior in decaying annular swirl flow with flow visualisation experiments were conducted to observe the behavior of the flow using an electrochemical method by Yapici (1985).

Kang et al. (2002) experimental and visualization study about the correlation of mass transfer coefficient for ammonia–water bubble absorption by varying orifice diameter, liquid concentration and vapor velocity are considered as the key parameters. A heat and mass transfer study conducted by applying phenomenological theory to model the absorption of the R134a gas bubble in liquid R134a–dimethyl formamide (DMF) solution, using MATLAB by Suresh and Mani (2010). The bubble dynamics during bubble growth have been studied using this model. Liquid concentration, temperature, heat and mass transfer rates, local heat and mass transfer coefficients are estimated at the bubble interface. Absorption rate, coupled heat transfer rate, average heat and mass transfer coefficients over the entire bubble life span are also calculated. Experimental investigations have been carried out to visualize bubble behaviour and effect of gas flow rate and liquid concentration on bubble characteristics of R134a) in liquid R134a– DMF solution in a glass absorber by Suresh and Mani (2012) in still and flowing solution. Similar type of study with tangential nozzle is studied experimentally for air-water in a bubble absorber. Bubble behaviour was studied in still, co-current and counter-current flow of water in the bubble absorber by Panda and Mani (2014) with the variation of air and water flow rate.

2.Solution Methodology

3D cylindrical coordinate mesh created for the bubble absorber by using commercial software. An unstructured mesh with quality of 0.73 and aspect ratio of 18 taken, have been used for numerical analysis. Finite-volume method is used for grid discretization of the absorber model domain. The mesh size of circumferential direction is uniform, but in the radial distribution is increasing the number of elementary volumes to get close result and minimizing the wall effect on the flow. Schematic diagram and the mesh topology of bubble absorber are shown in fig. 1. A cylindrical tube of 65 mm ID and 70 mm OD have been used for the absorber. Two injected nozzle of 4.8 mm ID and 6 mm OD used at an angle of 30° to the vertical axis and parallel to the azimuthal axis.

In this study, R134a-DMF solution is flowing in the main pipe and R134a vapour is injected through the tangential nozzle. Pressure based solver with steady state condition has been used for solving the problem. Grid independent study has been carried with four different types of mesh sizes say, 153, 251, 315, 555 thousands. Among the mesh sizes 315 thousand mesh size shows good result for heat and mass transfer study as shown in Table-1. An UDF (user defined function) is defined for the fluid property of both liquid and vapour phase like density, viscosity, specific heat and mass diffusivity which varies with the temperature. The correlations of fluid property present in the available literature are used to create the UDF. For solving the governing equation mixture multi-phase, k-ω SST turbulent model, Energy and Species transport model used. Mixture multi-phase model is used with an implicit scheme and PRESTO (Pressure Staggered option) scheme to solve the pressure term. In species transport model, R134a vapour is taken as secondary phase and R134a-DMF liquid used as primary phase. In the absorber model mass inlet boundary condition is used for liquid solution and vapour inlet, pressure outlet condition used at the outlet, no-slip condition in wall used for the model. A constant heat flux boundary condition used in the interface of the absorber. Mass flow rates of liquid and vapour, solution pressure, vapour pressure, temperature, species fraction and volume fraction given for the both liquid and vapour as initial condition. Operating pressure and temperature are set as per the problem. A negative gravity force acting in the y-direction as the position of bubble absorber. SIMPLE (Semi-implicit method for pressure linked equation) scheme is used for pressure-velocity coupling and second order upwind scheme is used for solving momentum, energy, volume fraction and species equation. Under relaxation factor used as per the solution convergence criteria. The steady simulation is carried out with a time step of varying 10^{-3} to 10^{-4} seconds and 20 iteration steps per time steps.

Table-1 Grid independent study

Grid size	1.53 lakh	2.51 lakh	3.15 lakh	5.5 lakh
Pressure drop (Pascal)	7593.7	7553.5	7541.1	7795
% deviation	---	0.53	0.69	-2.65

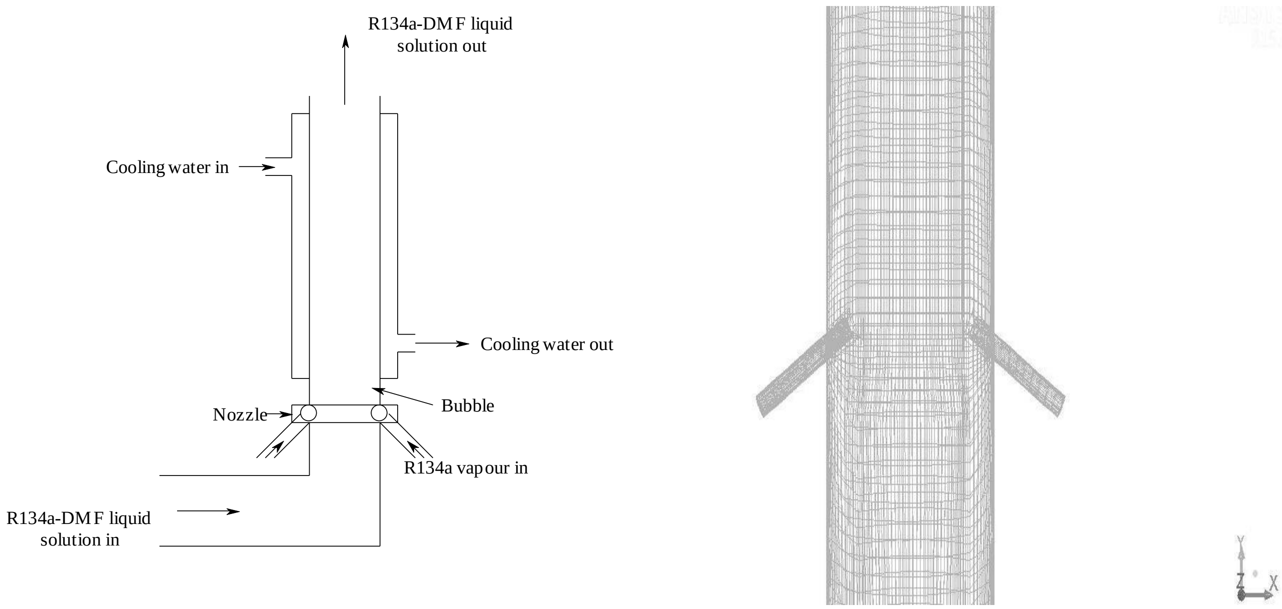

Figure 1 Mesh topology of the bubble absorber

3.Results and Discussions

Tangential injection model was simulated and compared with the single vertical nozzle injected to the bubble absorber containing R134a- DMF fluid combination reported by Suresh and Mani (2010). The model has been studied under the following operating condition such as initial condition as solution pressure 150 kPa to 400 kPa, solution mass flow rate 0.05 to 0.2 kg/s, Solution temperature 293 to 333 K, Solution initial concentration 0.2 to 0.4 kg/kg, Gas flow rate 0.001 to 0.004 kg/s, Gas temperature 273 K, Gas concentration 0.99 kg/kg, Constant wall flux of 1 kW have been maintained in the wall to predict the results accurately.

Continuous gas injected to the bubble absorber to generate bubble in the liquid-vapor interface. Initially the bubble grows to a maximum volume against the liquid pressure, detach from the nozzle moves upwards and collapse after some distance. At nozzle interface the bubble volume reduces to zero and new bubble growth starts, reaches to maximum volume, and thus the cycle of bubble dynamic continues in the absorber. At higher gas flow rate, the bubble dynamic does not occur at higher frequency, like bubble growth from a minimum volume to a maximum volume, detachment and collapse. The bubble diameter continuously increases till the bubble interface reaches equilibrium conditions and then, replaced by new bubble. The Bubble interference is considered when the bubble is detached from the nozzle. The interface parameter has been taken into account for the performance study of the bubble absorber.

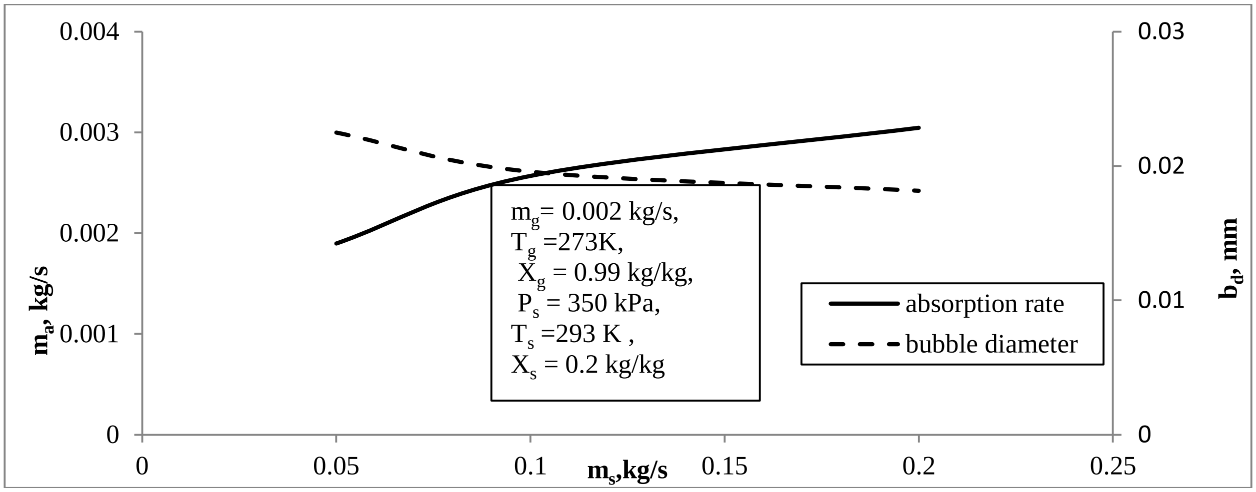

Figure 2 Effect of solution flow rate on bubble diameter and absorption rate

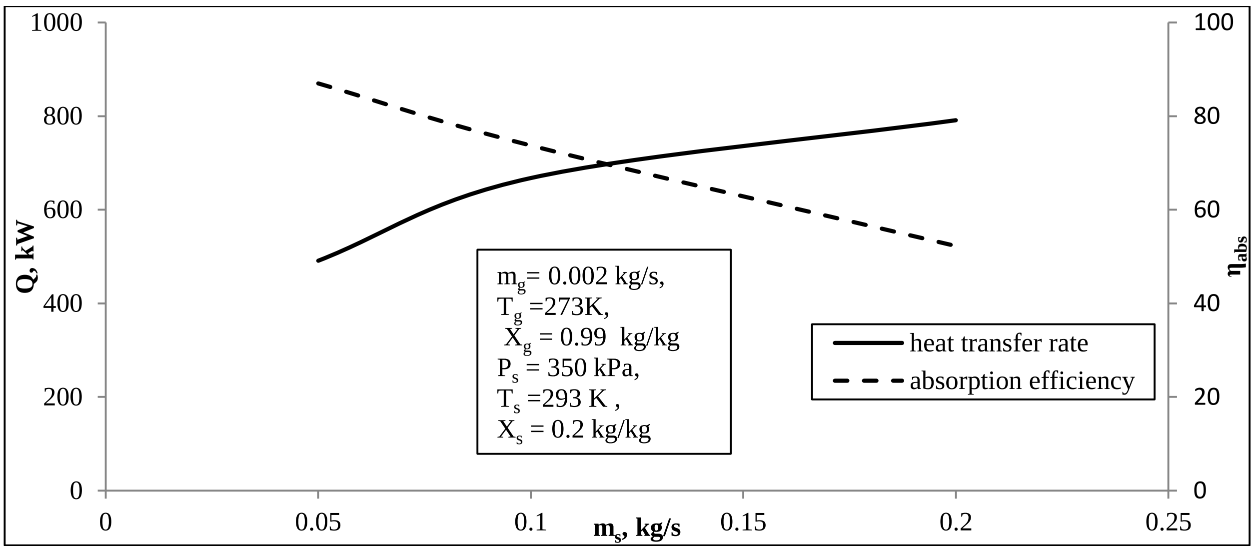

Figure 3 Effect of solution flow rate on heat transfer rate and absorption efficiency

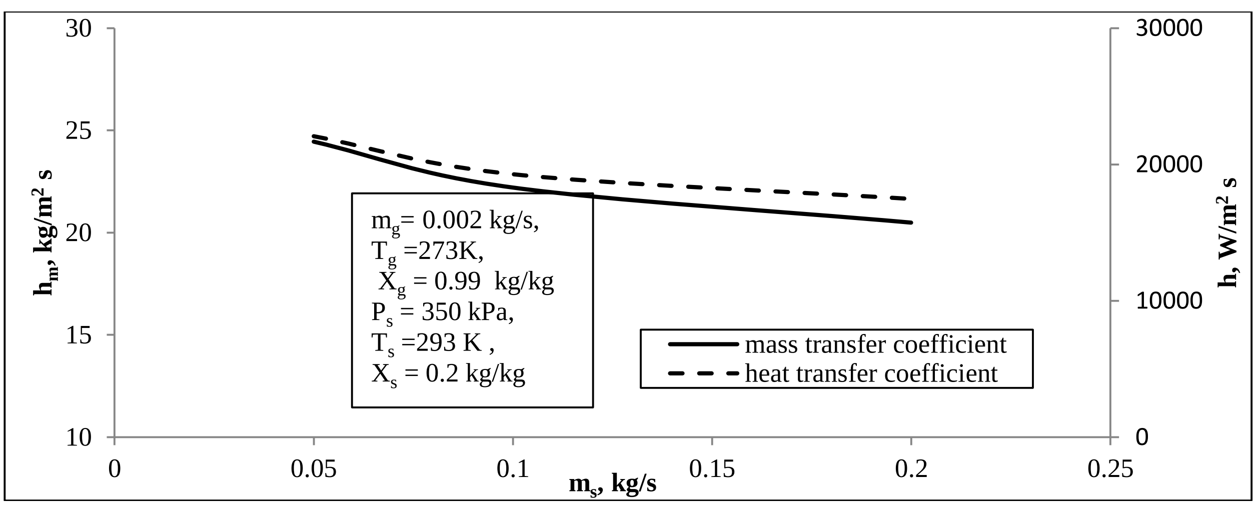

Figure 4 Effect of solution flow rate on mass transfer coefficient and heat transfer coefficient

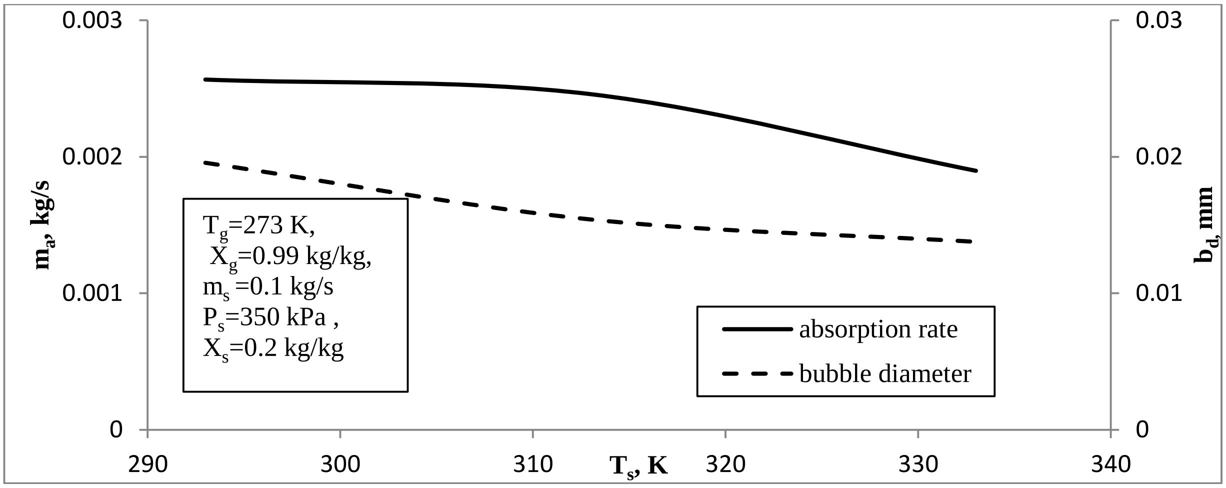

Figure 5 Effect of solution temperature on bubble diameter and absorption rate

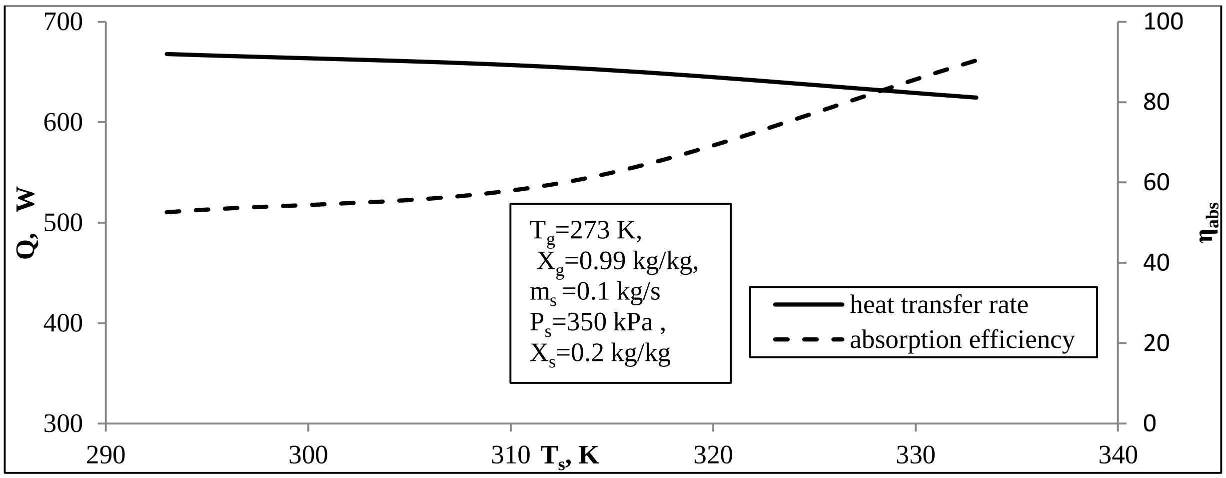

Figure 6 Effect of solution temperature on heat transfer rate and absorption efficiency

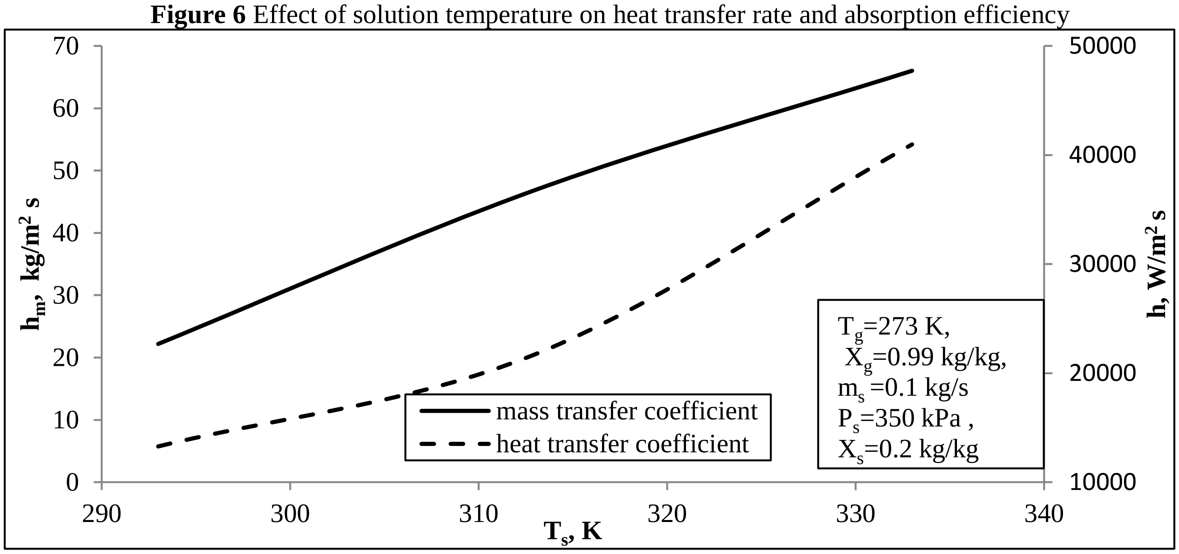

Figure 7 Effect of solution temperature on mass transfer coefficient and mass transfer coefficient

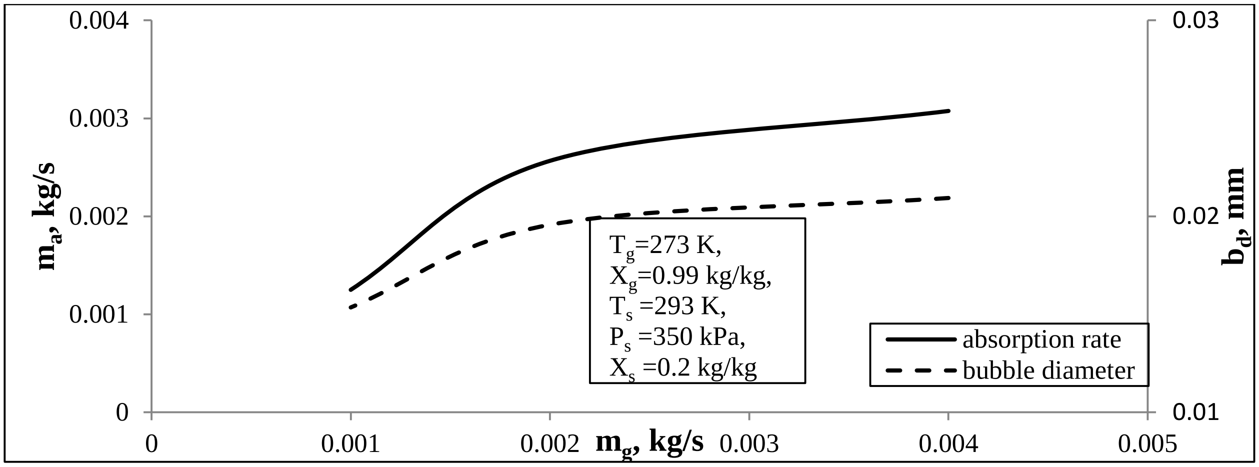

Figure 8 Effect of gas flow rate on bubble diameter and absorption rate

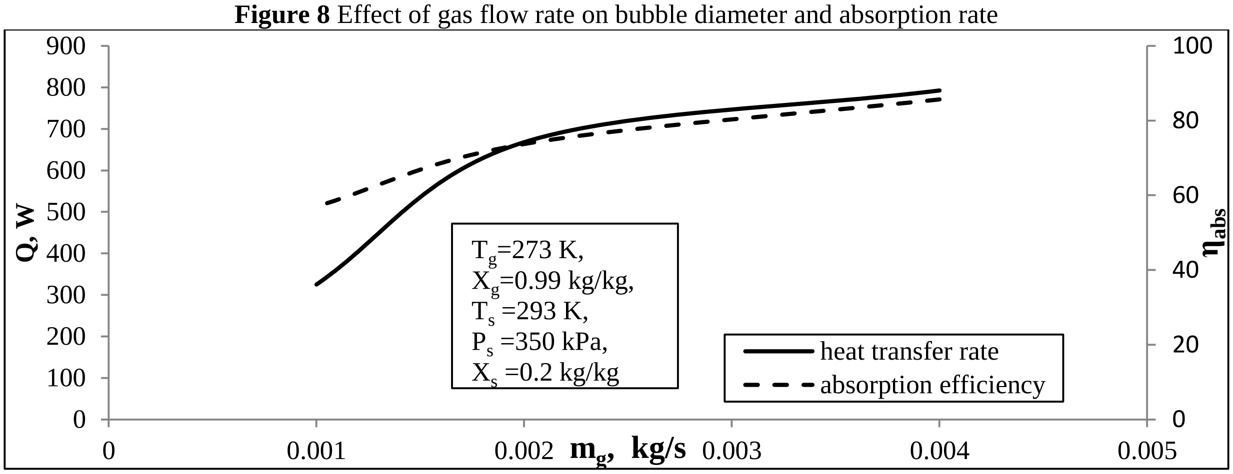

Figure 9 Effect of gas flow rate on heat transfer rate and absorption efficiency

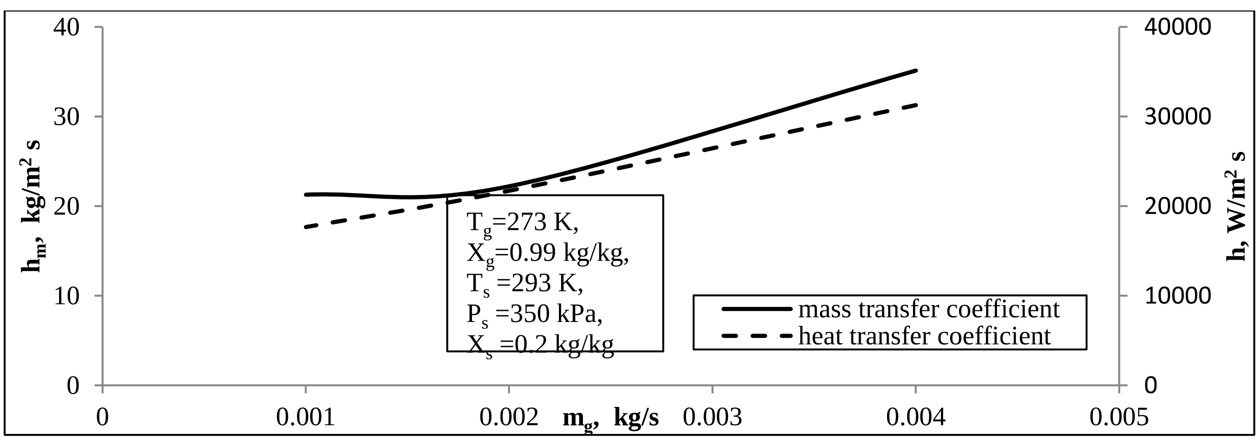

Figure 10 Effect of gas flow rate on mass transfer coefficient and heat transfer coefficient

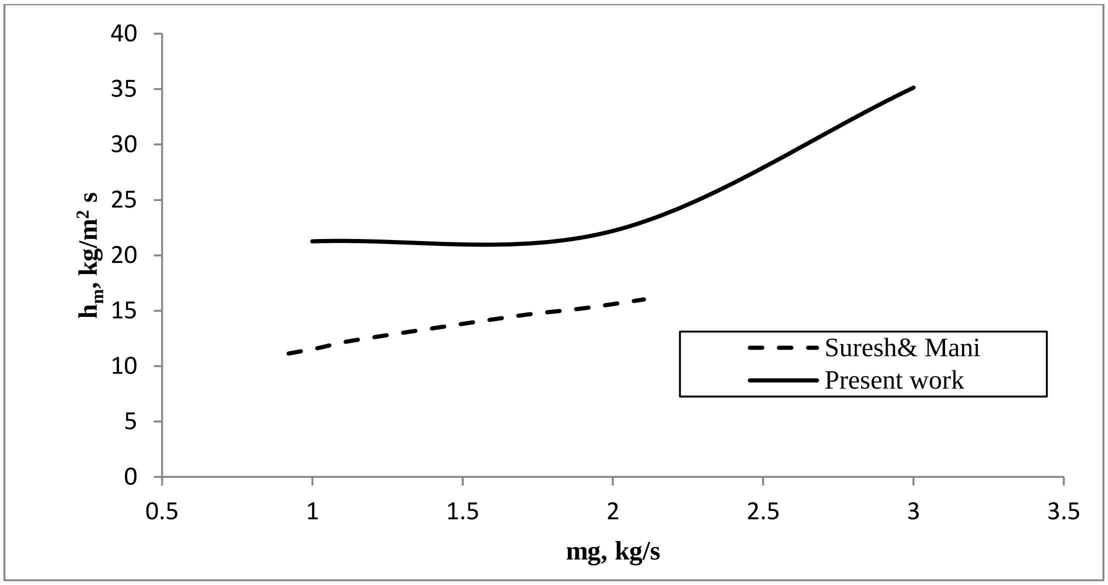

Figure 12 comparisons of mass transfer coefficient with variation with gas flow rate

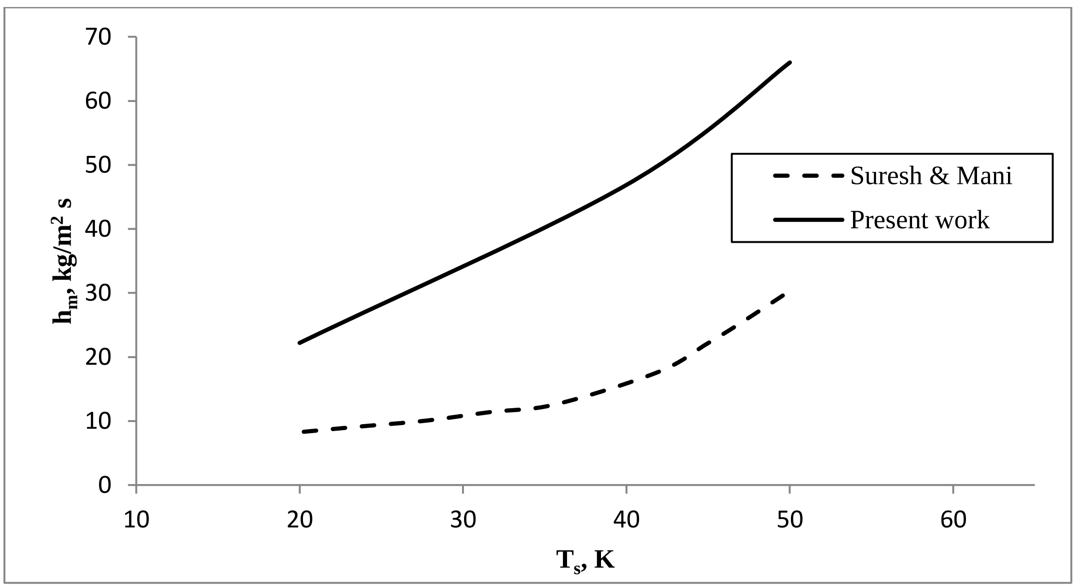

Figure 12 comparisons of mass transfer coefficient with variation with solution inlet temperature

Figure 2 shows variation of bubble diameter with solution flow rate at the given concentration of solution. As solution flow rate increases, bubble diameter starts decreasing. When liquid solution is flowing in upward direction, it exerts force on bubble surface and assists in earlier detachment. The increase in solution flow rate, increases the velocity reduces the bubble life, leads to an early detachment rate therefore the bubble diameter reduces. Figure 2 also shows solution flow rate variation of absorption rates at a given concentration of solution. As solution flow rate increases, absorption rate increases due to decrease in bubble life. Figure 3 presents change in heat transfer rates with solution flow rate at a given concentration of solution. As solution mass flow rate increases, heat transfer rate increases. The rate of increase of heat transfer depends on proportional rate of change in absorption rate. The absorption efficiency varies with solution flow rate at same concentration of solution shown in Fig. 3. The initial concentration increases in solution at absorber pressure outlet, as solution pressure increases the concentration decreases which in turn decreases the absorption efficiency. Variation of heat transfer coefficient with solution flow rate at a given concentration solution is shown in Fig 4. Heat transfer coefficient decrease solution flow rate increases due to increase in temperature of bubble volume. The mass transfer coefficient also reported in Fig. 4 varies with solution flow rate at an initial concentration of solution. Though absorption rate is high, mass transfer coefficient decreases as solution flow rate increases due to increase in concentration of bubble volume.

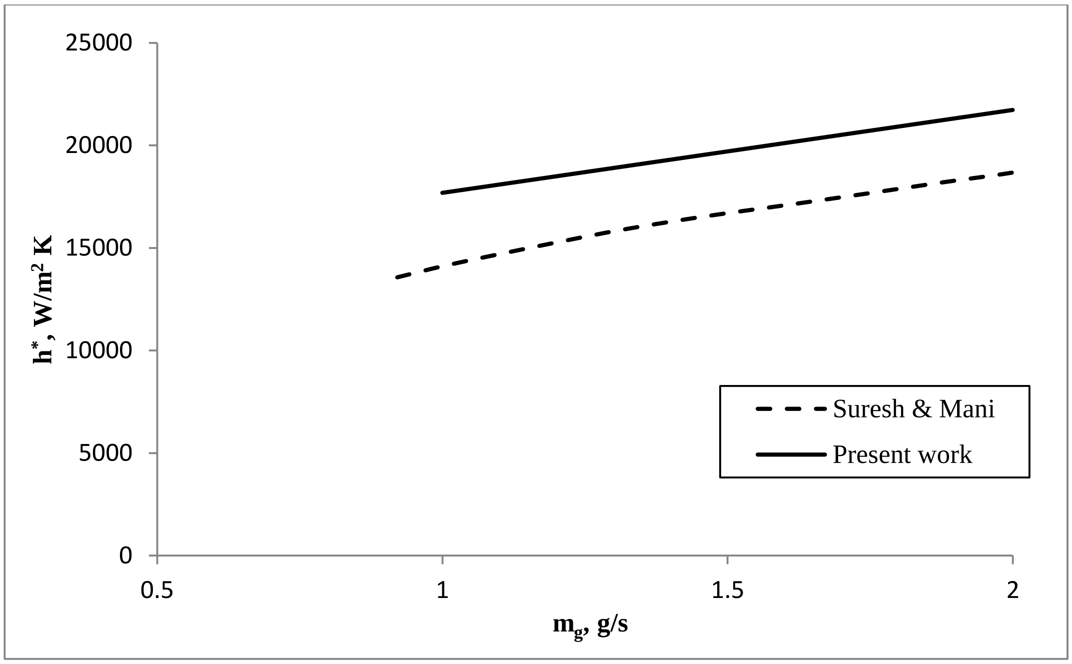

Figure 13 comparisons of heat transfer coefficient with variation with gas flow rate

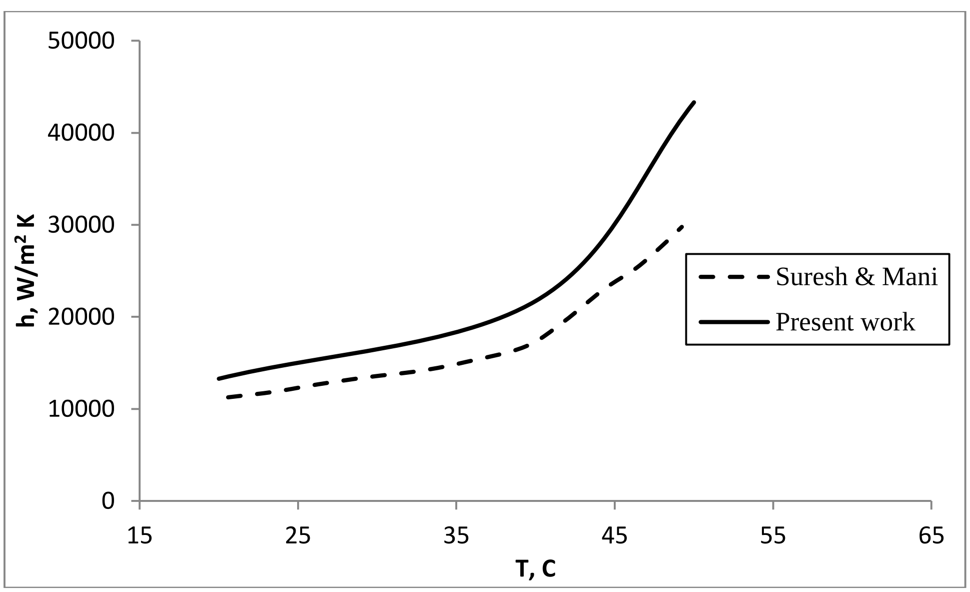

Figure 14 comparisons of heat transfer coefficient with variation with solution inlet temperature

In Fig. 5 bubble diameter and absorption rate decreases as the solution inlet temperatures increase due to reduction in bubble life. In Fig. 6 the heat transfer rate decreases with higher solution inlet temperatures due to lower absorption rate and absorption efficiency increases with solution inlet temperature due to reduction in bubble diameter, as solution inlet temperature increases due to reduction in mass fraction at bubble interface. Figure 7 presents the variation of heat transfer coefficient with solution inlet temperature, heat transfer coefficients increases with increase solution inlet temperatures because decrease in bubble volume and interface temperature dominates over the decrease in the heat transfer rate. Figure 7 also presents the mass transfer coefficient increases with solution inlet temperatures. Similar to the heat transfer coefficient at increasing in solution inlet temperatures, reduction in bubble volume and bubble diameter and concentration the absorption rate is less.

In Fig. 8 bubble diameter increase as gas mass flow rate increases and at higher gas flow rate it remains same. Absorption rate increase as the gas flow rate increase reported. In Fig. 9 heat transfer rate increases as gas mass flow rate increases due to higher absorption rates. Absorption efficiency increases at higher gas mass flow rates due to increase in liquid mass fraction at absorber outlet at higher absorption rates. In Fig. 10 the heat transfer coefficient also increases with higher gas flow rates due to increase in coupled heat transfer rate at higher absorption rates. Figure 10 represents variation of mass transfer coefficients with gas mass flow rate. The mass transfer coefficient increases with gas mass flow rates due to the increase in absorption rate at higher gas mass flow rates. The comparison of mass transfer coefficient varies in Fig. 11 and heat transfer coefficient in Fig. 13 with solution inlet temperature which compared with no swirl single vertical nozzle injection with the tangential nozzle induced swirl. Similarly the mass transfer coefficient shown in Fig. 12 and heat transfer coefficient in Fig. 14 varies with gas flow rate which compared the above condition. There is an enhancement of mass transfer coefficient of range 120-170% and heat transfer coefficient improvement of 20-40% predicted.

4.Conclusions

A numerical study of heat and mass transfer is applied to model with generating swirl by tangential injection to absorb the refrigerant R134a bubble in dimethyl formamide (DMF) solution. The properties like specific heat, density, viscosity, etc for R134a–DMF solution have been calculated as function of temperature using correlations available in literature. Bubble diameter, heat and mass transfer rates, heat and mass transfer coefficients, absorption rate, heat transfer rate, heat and mass transfer coefficients are calculated for the bubble absorber. The heat and mass transfer rates obtained from this model are compared with the single vertical nozzle inserted to the bubble absorber results. The results are in good agreement with the predictions of the model. The mass transfer coefficient enhancement is 120-170% and heat transfer coefficient enhancement of 20-40% in swirl flow compared to the no swirl case vertical nozzle inserted to the bubble absorber results found. Similar enhancement rate in heat transfer coefficient in Bali (1998) and Salimpour (2012) and mass transfer coefficient also reported in Yapici et al. (1994) and Shoukry et al. (1985).

Heat and mass transfer rates increase with the solution flow rate. Heat and mass transfer coefficients decrease as the solution flow rate increases Absorption efficiency decreases as solution flow rate increases. Heat and mass transfer rates decrease and heat, mass transfer coefficients and absorption efficiency increase as solution inlet temperature increases. Heat and mass transfer rates, heat and mass transfer coefficients and absorption efficiency increase as gas flow rate increases.

5.References

1) Algifri A. H., and Bhardwaj R. K., (1985). Prediction of the heat transfer for decaying turbulent swirl flow in a tube, *Int. J. Hear Mass Transfer.* Vol. 28, No. 9, pp. 1637-1643.
2) Bali Tfilin, (1998). Modeling of heat transfer and fluid flow for decaying swirl flow in a circular pipe, Int. *J. Hear Mass Transfer.* Vol. 25, No. 3, pp. 349-358.
3) Chang F., Dhir V.K. (1995). Mechanisms of heat transfer enhancement and slow decay of swirl in tubes using tangential injection, Int. *J. Heat and Fluid Flow,* vol. 16, pp. 78-87.
4) Guo Z., Dhir V.K. (1994). Single- and two-phase heat transfer in tangential injection- induced swirl flow, *Int. J. Heat and Fluid Flow*, vol. 10, No-3, pp. 203-210.
5) Kanga Yong Tae, Naganob T., Kashiwagib Takao, (2002) Mass transfer correlation of NH_3–H_2O bubble absorption, *International Journal of Refrigeration* 25, 878–886.
6) Kioth Osami (1990). Experimental study of turbulent swirling flow in a straight pipe, *Journal Fluid Mech*., vol. 225, pp. 445-479.

7) Kreith Frank, Sonju O.K. (1965). The decay of a turbulent swirl in a pipe, *Journal Fluid Mech*. Vol. 22 part2 pp. 257-271.
8) Lelea Dorin (2010). Effects of inlet geometry on heat transfer and fluid flow of tangential micro-heat sink, *International Journal of Heat and Mass Transfer* 53, 3562-3569.
9) Martemianov S., Okulov V.L.(2002). Mass transfer ambiguities in swirling pipe flows, *Journal of Applied Electrochemistry* 32, 25–34.
10) Martemianov S., Okulov V.L.(2004). On heat transfer enhancement in swirl pipe flows, *International Journal of Heat and Mass Transfer* 47, 2379–2393.
11) Panda Santosh Kumar, Mani A. (2014), Bubble dynamics study with tangential nozzles in a bubble absorber, *International Sorption Heat Pump Conference at Maryland University*, Maryland, March 31-April 04,2014.
12) Salimpour M.R., Yarmohammadi S., (2012) Heat transfer enhancement during R-404A vapor condensation in swirling flow, *International Journal of Refrigeration* XXX, 1-8.
13) Shoukry Ehsan, Shemllt Leslle W., Mass transfer enhancement in swirling annular pipe flow, Ind. Eng. Chem. Process Des. Dev., Vol. 24, no. 1, 1985.
14) Suresh M., Mani A. (2010), Heat and mass transfer studies on R134a bubble absorber in R134a/ DMF solution based on phenomenological theory, *International Journal of Heat and Mass Transfer* 53, pp. 2813-2825.
15) Suresh M., Mani A. (2012), Experimental studies on bubble characteristics for R134a–DMF bubble absorber, *Experimental Thermal and Fluid Science* 39 (2012) 79–89
16) Yapici S., Patrick M. A., Wragg A. A., (1994). Hydrodynamics and mass transfer in decaying annular swirl flow, *Int. Comm. Heat Mass Transfer*, Vol. 21, pp. 41-51.

Nomenclature

M	Mass flow rate, kg/s	η_{abs}	Absorption efficiency
T	Temperature, K	h	Heat transfer coefficient, W/m^2 K
P	Pressure, kPa	h_m	Mass transfer coefficient, kg/m^2 s
X	Concentration , kg/kg	m_a	Absorption rate, kg/s
b_d	Bubble diameter, m	g	gas
Q	Heat transfer, W	s	solution