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ABSTRACT

A model has been developed based on Colburn - Drew type formulation to analyze a vertical tube in tube stainless steel generator with forced convective boiling. Desorption of refrigerant vapour from refrigerant-absorbent solution takes place in the inner tube of the generator, when hot water through the annulus is used as heating medium. Simultaneous heat and mass transfer phenomena of desorption are described mathematically using the mass and energy balances, considering the heat and mass transfer resistances in liquid as well as vapour phases. Model equations are solved simultaneously by means of initial value problem solvers using explicit Runge-Kutta method with 4th order accuracy. A computer code has been developed in MATLAB to obtain the results. A parametric analysis has also been performed to study the effect of various parameters on the performance of the generator.

1. INTRODUCTION

Among the various types of refrigeration systems, vapour absorption refrigeration system (VARS) has attracted a renewed interest due to its ability to use the low grade energy like solar energy, waste heat source, etc. Traditional VAR systems were developed with ammonia-water as the working fluid. Due to the toxicity of ammonia, attention has been moved to new working fluids. Among them, CFCs and HCFCs are being phased out by Montreal and other International Protocols. HFCs, even though do not contribute to ozone depletion, still contribute to global warming. Hence ammonia-water mixture is revived and used as the leading working fluid in the absorption systems.

In the absorption system, generator is considered one of the important components and there is scope for improving its performance, which will contribute to the performance of the absorption system itself. In order to achieve better performance of the generator, the numerical study of generator is carried out to evaluate the performance of the generator and is presented in this paper.

The boiling process in generator is characterized by simultaneous heat and mass transfer phenomena. These phenomena have to be analyzed to understand the desorption process. Bennett and Chen (1980) studied the forced convective boiling with aqueous ethylene glycol solutions and developed a correlation to predict the heat transfer coefficient. This correlation improved the understanding of flow boiling of binary mixtures. Mishra *et al.* (1981) made an experimental investigation on forced convective evaporation of the CFC refrigerant mixtures R22/R12 inside horizontal tubes and obtained correlations to predict the heat transfer coefficients for each mixture separately. Ross *et al.* (1987) determined the experimental heat transfer coefficients for horizontal flow boiling of pure R152a and R13Bl and for four mixtures of these refrigerants and compared with existing correlations. The correlative evidence suggested that full suppression of nucleate boiling is easier to achieve with mixtures than pure fluids. Jung *et al.* (1989) conducted an experimental study on horizontal flow boiling heat transfer for pure R22, R 114 and their mixtures under uniform heat flux condition and obtained more than 1200 local heat transfer coefficients for annular flow at a reduced pressure. A full suppression of nucleate boiling has been observed for both pure and mixed refrigerants at qualities above 10 - 30 %. Celata *et al.* (1993) performed experiment on binary mixtures of the CFC refrigerants R12/R114 in up flow forced convective boiling and found that the results were in good agreement with the Bennett - Chen correlation. Rivera *et al.* (1999) studied the heat transfer in forced convective boiling experimentally for the water/ammonia and ammonia/ lithium nitrate mixtures in a vertical tube. Correlations were proposed to correlate the experimental local heat transfer coefficients for the above mixtures. Barbosa *et al.* (2001) proposed a model for phase change heat transfer to binary mixtures at high qualities (annular flow regime) and

compared with the experimental data on literature. The model was based on Colburn and Drew (1937) formulation originally employed for the condensation of mixed vapours. Convective boiling of ternary mixtures in vertical tubes was dealt with experimentally to measure bulk and wall temperatures as well as local heat transfer coefficients (Barbosa *et al.*, 2002). It was found that the deterioration in the heat transfer coefficient was due to a combined effect of droplet interchange and mass transfer resistance in the vapour side. Khir *et al.* (2005) performed an experiment on the forced convective boiling heat transfer of ammonia-water mixtures inside a vertical tube. The experimental data were compared with the available correlations. Jaime Sieres *et al.* (2007) simulated the heat and mass transfer processes of a packed rectification column for ammonia-water absorption system and compared with experimental data. In this paper, a model is developed based on Colburn-Drew formulation to simulate desorption of refrigerant vapour from the refrigerant - absorbent strong solution in a vertical tubular generator. The model is validated using ammonia - water mixtures and the results are compared with experimental results from the literature.

2. MATHEMATICAL MODEL

A mathematical model for the forced convective boiling of refrigerant-absorbent mixtures in vertical tubular generator is developed. The generator is made up of two stainless steel coaxial tubes of 1m length as shown in Fig.1. The inner and outside diameters of the inner tube are 20 and 23 mm respectively. The strong solution of refrigerant-absorbent mixture from the absorber enters from bottom of the inner tube of the generator. The hot water, which is used as the heating source, is sent from the top through the annulus of the system. The inner and outer diameters of the external tube are 28 and 31 mm respectively. The strong solution enters the tube at bubble point temperature for the given pressure and concentration of the solution. Hence boiling takes place in the tube and vapour is generated from the strong solution.

The generator tube is divided into 100 elements. The schematic of a differential control volume is illustrated in Fig.2. Mass and energy balances are considered for each element. In order to consider the heat and mass transfer resistances in liquid as well as vapour phases, heat and mass transfer equations are formulated for each phase. The following assumptions are considered for the liquid and gas medium: (a) Process is assumed to be in steady state and flow is one dimensional; (b) Transport properties are considered constant; (c) Heat and mass transfer resistances are assumed to lie in a thin layer close to interface; heat and mass transfer areas are equal; (d) Thermodynamic equilibrium exists at the liquid vapour interface; (e) No chemical reactions are considered.

2.1 Heat transfer equations
Heat and mass transfer takes place simultaneously in the liquid and vapour phases. Heat transfer from the hot water to the vapour phase takes place in two stages, (i) From hot water to the liquid phase through the wall and (ii) from the liquid phase to the vapour phase across the interface. Total energy transferred based on control volume may be given as

$$Q_h = d(m_L H_L) + d(m_V H_V) \tag{1}$$

Energy transferred to the liquid phase comprises of latent and sensible heats. Latent heat is utilized for evaporation of components of the solution whereas sensible heat is supplied as convective and conductive flux to raise the temperature of the solution from T_L to T_i and from T_L to $T_L + \Delta T_L$ respectively. Thus the total heat transfer from the liquid phase to the liquid interface is given by

$$Q_h = d(m_L . H_L) + (\dot{m}_R . H_{R(L)i} + \dot{m}_A . H_{A(L)i} + \dot{h}_L (T_L - T_I)). A_{si} \tag{2}$$

$$\text{where} \quad \dot{h}_L = h_L . (\frac{\phi_L}{1 - e^{-\phi_L}}) ; \phi_L = \frac{(\dot{m}_R . Cp_{R(L)} + \dot{m}_A . Cp_{A(L)})}{h_L} \quad \text{and} \quad \dot{m} = \frac{m}{A_{si}} \tag{3}$$

In the similar manner, the total heat transfer from the vapour interface to the vapour phase is given as

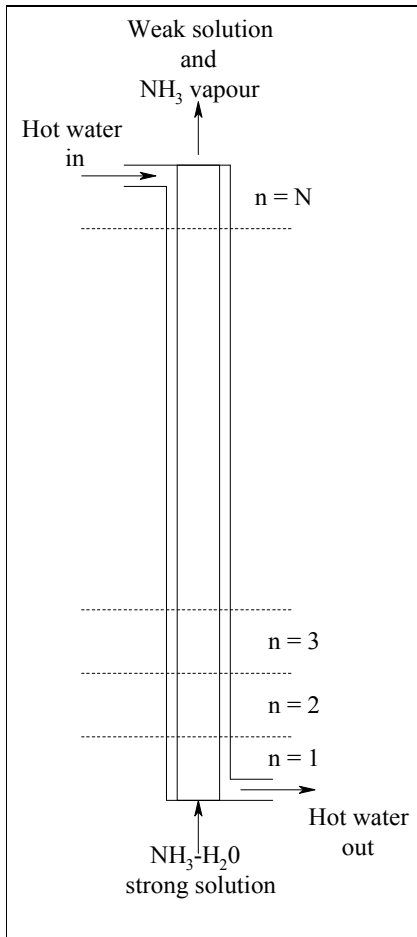$$d(m_V . H_V) = (\dot{m}_R . H_{R(V)i} + \dot{m}_A . H_{A(V)i} + \dot{h}_V (T_I - T_V)). A_{si} \tag{4}$$

Weak solution
and
NH₃ vapour

Hot water
in

n = N

n = 3

n = 2

n = 1

Hot water
out

NH₃-H₂0
strong solution

Fig.1. Schematic of the tubular generator

Hot water in
m_h
T_h

Liquid
$m_L + dm_L$
$H_L + dH_L$
$x - dx$

Vapour
$m_V + dm_V$
$H_V + dH_V$
$y + dy$

Q_h

$Q_{L,sensible}$
+
$Q_{L,latent}$

$Q_{V,sensible}$
+
$Q_{V,latent}$

dz

$(m_{NH3} + m_{H20})_L$

$(m_{NH3} + m_{H20})_V$

Interface

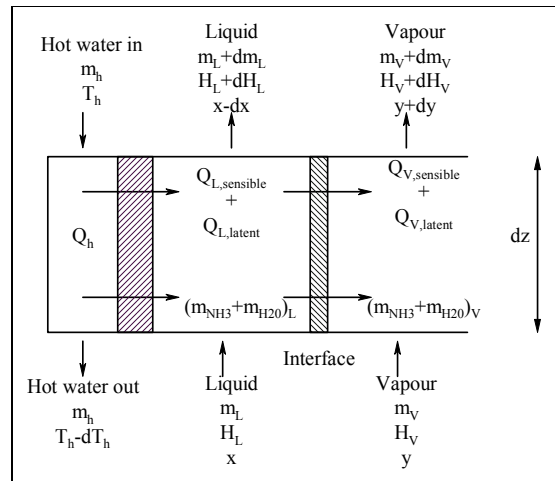Hot water out
m_h
$T_h - dT_h$

Liquid
m_L
H_L
x

Vapour
m_V
H_V
y

Fig.2. Elemental control volume of generator

Energy flux balance at the liquid-vapour interface gives

$$\dot{m}_R . H_{R(L)i} + \dot{m}_A . H_{A(L)i} + \dot{h}_L (T_L - T_I) =$$

$$\dot{m}_R . H_{R(V)i} + \dot{m}_A . H_{A(V)i} + \dot{h}_V (T_I - T_V)$$

(5)

Heat supplied by the hot water could be obtained from the Effectiveness - NTU method as

$$Q_h = \varepsilon . C_{min} . (T_h - T_L) \qquad \text{where,} \qquad U = f(h_h, K_w, h_L)$$

(6)

C_{min} and C_{max} are found from mass flow rates and specific heats of the hot water and boiling mixtures.

2.2 Mass transfer equations
Mass flux transfer between the liquid and vapour phases takes place due to the combined effect of bulk transport and molecular diffusion of mixture across the interface. The mass flux desorbed from the bulk liquid to the liquid interface is evaluated as (Bird *et al.*, 1960)

$$\dot{m}_R = \rho_L \beta_L z \ln(\frac{z - x_I}{z - x_B}) \quad \text{where} \quad z = \frac{\dot{m}_R}{\dot{m}_I} ; \quad \dot{m}_I = \dot{m}_R + \dot{m}_A \tag{7}$$

Similarly the mass flux transferred from the vapour interface to the bulk vapour is obtained from

$$\dot{m}_R = \rho_V \beta_V z \ln(\frac{z - y_B}{z - y_I}) \tag{8}$$

Mass balance at the liquid-vapour interface results

$$\dot{m}_I \bigg|_L = \dot{m}_I \bigg|_V \tag{9}$$

2.3 Heat transfer coefficient

Many predictive correlations are available for forced convective boiling of mixtures. The most widely used method was proposed by Bennett and Chen and is given by (Celata *et al.*, 1993),

$$h_{mix} = h_{mac}.F_{mix} + h_{mic}.S_{mix} \tag{10}$$

In this, the heat transfer coefficient is contributed by the convective boiling (macroscopic) coefficient and the nucleate boiling (microscopic) coefficient with the corresponding enhancement (F_{mix}) and suppression (S_{mix}) factors respectively. The above correlation is used to predict the boiling heat transfer coefficient for the desorption process.

3. NUMERICAL TECHNIQUE

For the incremental control volume shown in Fig. 2, the conservation of mass, energy and concentration are given as

$$\frac{dm_V}{dz} = \dot{m}_I .Asi \tag{11}$$

$$\frac{dy_B}{dz} = (\frac{\dot{m}_R .Asi - dm_V . y_B}{m_V + dm_V}) \tag{12}$$

$$\frac{dm_L}{dz} = -\dot{m}_I .Asi \tag{13}$$

$$\frac{dx_B}{dz} = -(\frac{\dot{m}_R .Asi + dm_L . x_B}{m_L + dm_L}) \tag{14}$$

$$\frac{dH_L}{dz} = (\frac{Q_h - (\dot{h}_L(T_L - T_i) + \dot{m}_R .H_{R,L} + \dot{m}_A .H_{A,L}).Asi - dm_L .H_L}{m_L + dm_L}) \tag{15}$$

$$\frac{dH_V}{dz} = (\frac{(\dot{h}_V(T_i - T_V) + \dot{m}_R .H_{R,V} + \dot{m}_A .H_{A,V}).Asi - dm_V .H_V}{m_V + dm_V}) \tag{16}$$

$$\frac{dT_h}{dz} = (\frac{Q_h}{m_h .Cp_h}) \tag{17}$$

3.1 Initial and boundary conditions

The above model equations are solved using the initial and boundary conditions. The initial conditions are taken from the conditions of liquid and vapour phases and hot water respectively at the inlet of the first element. For the first element, quality of the mixture is assumed as 0.0001. At z = 0

$$m_L = 0.9999(m_{total}); \quad x_B = x_{B,in}; \quad T_L = T_{L,in}$$
$$m_V = 0.0001(m_{total}); \quad y_B = y_{B,in}; \quad T_V = T_{V,in} \tag{18}$$

For the assumed counter flow direction,

$$T_h = T_{h,out} \tag{19}$$

The boundary conditions are specified at the liquid-vapour interface

$$x_I = f(P, T_I); \quad y_I = f(P, T_I) \tag{20}$$

The above differential equations are solved simultaneously by means of initial value problem solvers using explicit Runge-Kutta method with 4th order accuracy. A computer code has been developed in MATLAB to obtain the results. Knowing the initial conditions, mass fluxes desorbed across the interface, mass flow rate, concentration and temperatures of the liquid and vapour phases and the hot water temperature are determined for the first element. In the every succeeding element, the outlet conditions of the preceding element are considered as the initial conditions and the iteration procedure is continued. The gas phase heat and mass transfer coefficients are evaluated from Dittus-Boelter equations. Liquid phase mass transfer coefficient is obtained using Chilton-Colburn analogy. The properties for the ammonia-water mixture in liquid phase have been calculated as functions of temperature, pressure and concentration for each element, using experimental correlations with 3-5% error (Reid *et al.*, 1989). The vapour mixture properties have been calculated using correlations from Ziegler and Trepp (1984) and M.Conde engineering (2006). The vapour phase enthalpy is calculated from the equations of Yokozeki (2005). The methodology for the simulation is detailed in the following algorithm:

    i.   Guess interface temperature, T_I and calculate x_I and y_I using equations (20)
    ii.   Fix z to satisfy mass balance equation (9)
    iii.   Fix T_I by satisfying energy balance at the interface, equation (5)
    iv.   Knowing the inlet conditions, model equations are solved for parameters.

4. RESULTS AND DISCUSSION

The model is validated using the ammonia-water mixture as the working fluid and the results have been compared with experimental results of Khir *et al.* (2005). Figure 3a shows the comparison between the average heat transfer coefficient predicted by the model and that obtained from the experiment. The agreement is found to be good with a deviation of 18.79 %. The heat transfer rate predicted from the model is compared with that determined from the experiment as shown in Fig. 3b with a difference of 8.24 %.
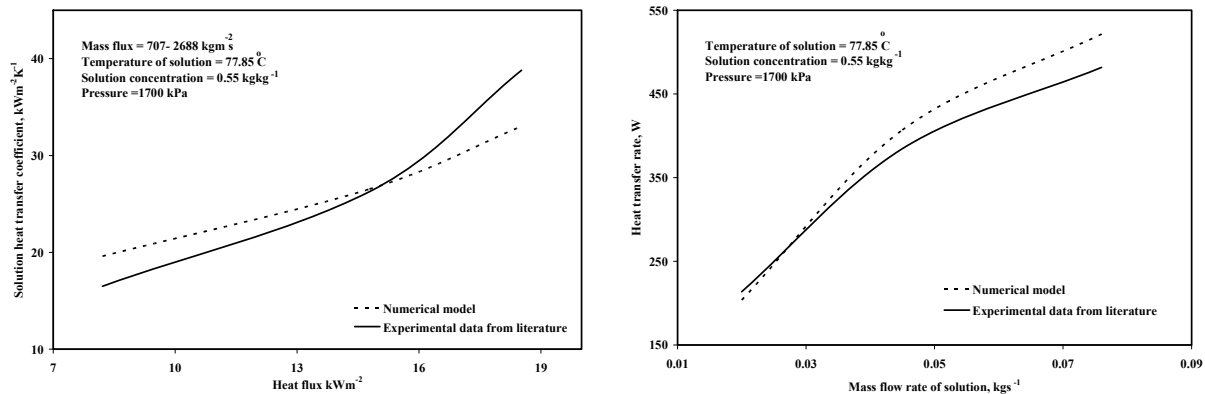

Fig. 3 Comparison of (a) heat transfer coefficient and (b) heat transfer rate between model and experiment

The performance of the vertical tubular generator is simulated for a range of heat flux (5500 – 6250 Wm^{-2}), Mass flow rate (0.01- 0.025 kgs^{-1}), Ammonia mass fraction (0.55 - 0.65 $kgkg^{-1}$) and Pressure (1700 - 1900 kPa). By solving the model equations, the values of mass flux desorbed, concentration and temperature profiles at the bulk

liquid, bulk vapour and liquid-vapour interface respectively, mass flow rate of liquid and vapour phases, average and overall heat transfer coefficients and quality are obtained for all the elements. The variation of these parameters along the length of the generator may be studied. Figure 4 shows the increase of mass flow rate of vapour, as desorption proceeds along the generator.
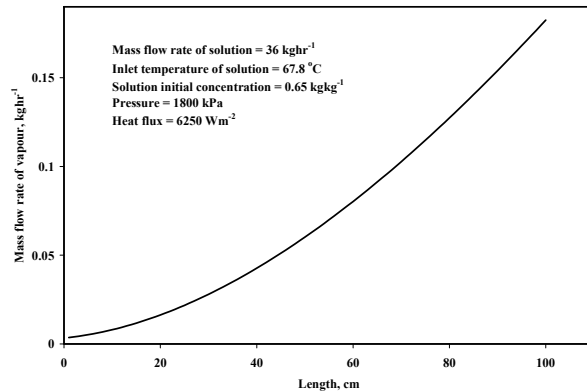

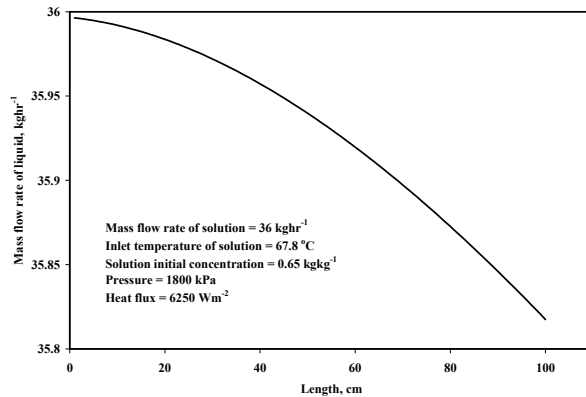Fig.4 Variation of mass flow rate of vapour along the generator

Fig.5 Variation of mass flow rate of liquid along the generator

At higher temperatures of hot water, the desorption rate is enhanced which results in the increasing trend of mass flow rate of vapour. For the same reason, the mass flow rate of liquid is found to decrease in the axial direction as shown in Fig. 5. The temperature profiles predicted at the bulk liquid, bulk vapour and at the liquid-vapour interface are plotted in Fig. 6. For the constant heat flux conditions, the liquid bulk temperature is always higher than the interface temperature which, in turn, is higher than the vapour temperature. From the figure, it is inferred that the liquid phase heat transfer resistance is playing a dominant role in the boiling process.
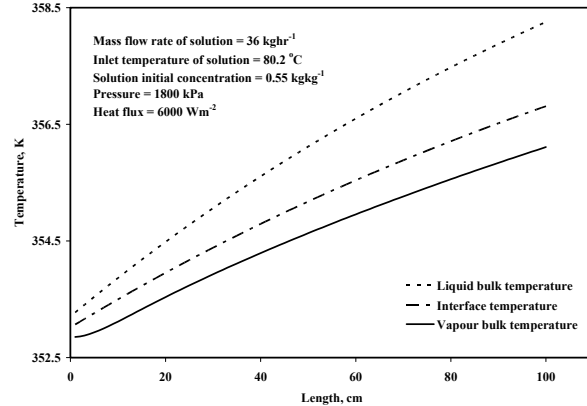

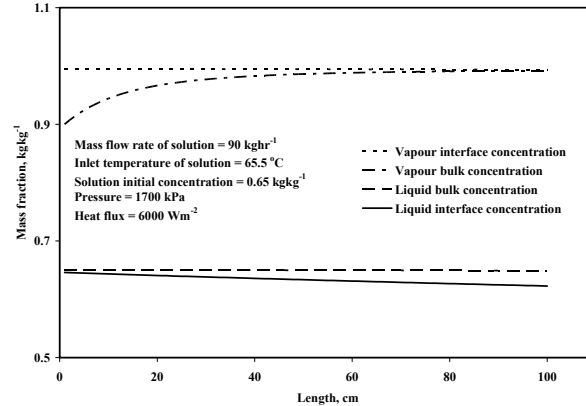Fig.6 Variation of temperatures along the generator during desorption process

Fig.7 Variation of ammonia concentration in liquid and vapour phases during desorption process

In Fig. 7, the concentration profiles are plotted as a function of length of the generator. In the liquid phase, it is observed that the bulk concentration is greater than the liquid interface concentration, whereas in the vapour phase, the vapour interface concentration is greater than the bulk concentration. It is inferred that the mass transfer resistances are dominant in liquid phase than in the vapour phase. These concentration gradients facilitate the mass transfer in two stages: first from the bulk liquid to liquid interface and then from the vapour interface to the bulk vapour. As desorption continues, the liquid bulk concentration decreases and the vapour bulk concentration increases. Parametric analyses have been carried out to study the influence of important parameters on the desorption process. The effect of generator pressure on the mass flux desorbed is presented in Fig. 8. Desorption rate increases with increase in pressure, for the same heat flux condition.
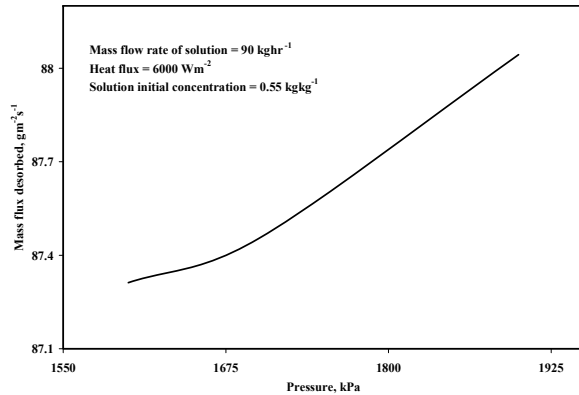
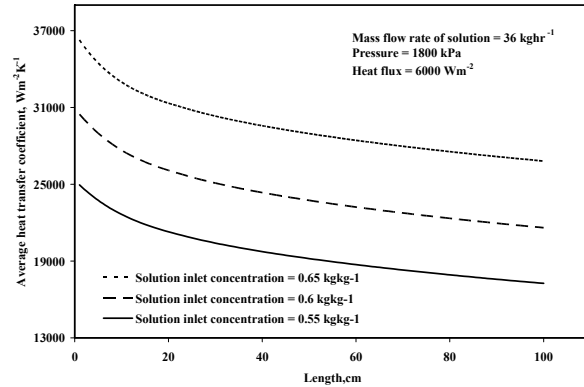Fig. 8 Effects of generator pressure on mass flux desorbed

Fig. 9 Variation of average heat transfer coefficient along generator at different concentration

The variation of average boiling heat transfer coefficient along the generator is illustrated in Fig. 9, at different mass fractions of solution. For the constant pressure condition, as the solution inlet concentration decreases, the solution inlet temperature increases resulting in suppression of nucleate boiling component. Since the nucleate boiling coefficient is the major contributor to the boiling heat transfer coefficient, there is a decrease in boiling heat transfer coefficient for the decrease in concentration. As the boiling temperature increases along the length, the nucleate boiling coefficient is suppressed and hence the decrease in the average heat transfer coefficient along the length. The effect of mass flow rate of solution on the convective average heat transfer coefficient at different generator pressures and solution inlet concentrations are depicted in Fig 10(a) and 10(b) respectively. Heat transfer coefficient increases with the increase in generator pressure and the mass flow rate of solution. Also it decreases with the decrease in solution concentration due to the effect of suppression of nucleate boiling as explained earlier.
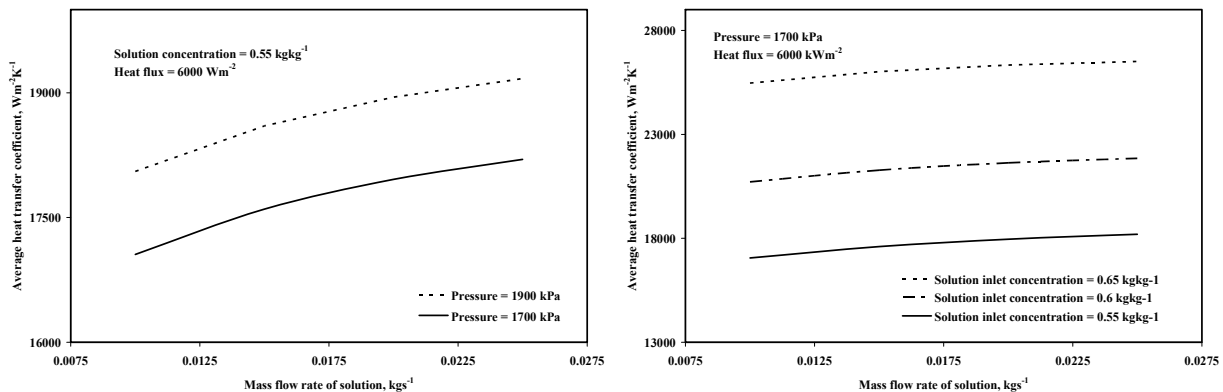

Fig. 10 Effect of mass flow rate of solution on boiling heat transfer coefficient at (a) different generator pressure and (b) different solution concentration

In Fig. 11, the effect of heat flux supplied on the heat transfer coefficient is shown for different values of solution inlet concentration. Heat transfer coefficient increases as the heat flux to the generator and the solution concentration increase. The variation of vapour temperature along the generator has been plotted in Fig. 12. At higher temperatures of hot water, the temperatures of the liquid and vapour phases are also found to be higher resulting in enhanced desorption rate. This is substantiated with the trends of increased mass flow rate of vapour, at higher values of hot water inlet temperatures.
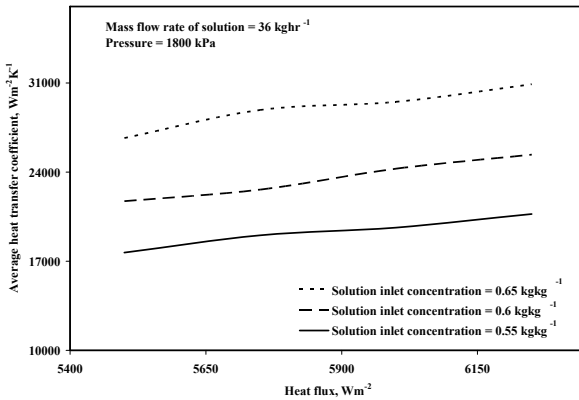
Fig.11 Effect of heat flux on heat transfer coefficient
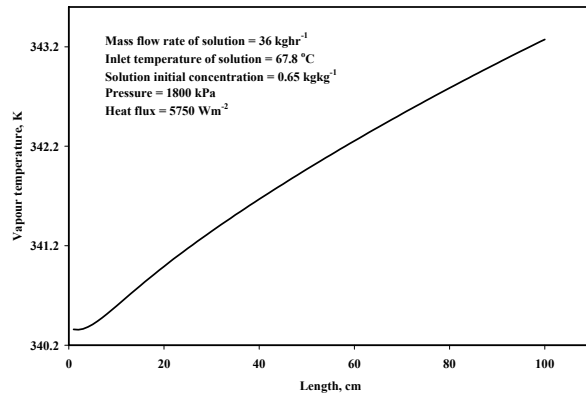at different solution inlet concentration

Fig. 12 Variation of vapour temperature along the
generator at different hot water temperatures

5. CONCLUSIONS

A numerical analysis of the forced convective boiling of refrigerant- absorbent solution in a vertical tubular generator has been carried out. Both liquid and vapour phase resistances are considered for the combined heat and mass transfer phenomena. Mass flow rate, concentration and temperature of the liquid and vapour phases, concentration and temperature at the liquid-vapour interface are calculated. Mass flux desorbed, average heat transfer coefficient, overall heat transfer coefficient and desorption rate are also estimated. Parametric studies are carried out to examine the effect of different parameters on the desorption process. Using the ammonia-water mixture, the model is validated and compared with the experimental results in the literature and the agreement is found to be good. The following are the conclusions drawn from the analysis: During desorption process, the bulk liquid concentration decreases and the bulk vapour concentration increases. Liquid phase mass transfer resistance plays a crucial role in this process. As far as the heat transfer is concerned, the nucleate boiling phenomenon is suppressed at higher boiling temperatures and desorption process is dominated by convective boiling phenomenon. Mass flow rate of vapour, average heat transfer coefficient and overall heat transfer coefficient increase and mass flow rate of liquid decreases, as the heat flux given to system increases. For a constant pressure condition, average heat transfer coefficient increases as the solution inlet concentration increases. Average heat transfer coefficient increases both with the generator pressure and the mass flow rate of solution. Desorption rate increases with increase in pressure and mass flow rate of solution

NOMENCLATURE

				Subscripts	
A_{si}	inner surface area of tube	(m^2)			
d	diameter of tube	(m)	A	absorbent	
h	heat transfer coefficient	$(Wm^{-2}K^{-1})$	B	bulk	
H	enthalpy	(Jkg^{-1})	h	hot water	
K	thermal conductivity	$(Wm^{-2}K^{-1})$	i	inner surface	
m	mass flow rate	(kgs^{-1})	i, I	liquid-vapour interface	
Q	heat supplied	(W)	L	liquid phase	
x	mass fraction in liquid phase	$(kgkg^{-1})$	o	outer surface	
y	mass fraction in vapour phase	$(kgkg^{-1})$	R	refrigerant	
z	axial coordinate	(m)	V	vapour phase	
Greek symbol			w	wall	
β	mass transfer coefficient	(ms^{-1})			

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