Journal of Advanced Science and Engineering Research Vol 3, No 3 September (2013) 226-242

# The Performance of a Falling Film Absorber Using Thin Wires

Article Info

Received: 3/5/2013
Accepted:11/7/ 2013
Published online: 1/9/2013

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ISSN 2231-8844

**Abstract**

The performance study of a falling film multi-vertical tube absorber has been extended and applied to multi vertical 1mm diameter wires in the present work. The heat and mass transfer equations have been solved numerically using finite difference method. The wires are assumed to be cooled on both/ or one end to conduct heat from the absorbent. Results were presented in terms of Lewis number, heat of absorption and cooling factor. The mass effectiveness was found to increase with increasing the Lewis number and reduce with increasing heat of absorption. The overall performance of 1 mm diameter wire-absorber has greatly increased compared with the larger diameter-tube absorber. The overall performances of a 5 dimensionless length-absorber of different tube radius (100 mm, 40 mm, 20 mm, 5 mm) were compared to that of 0.5 mm radius. The overall performance of the wire was found to be higher. In other words, an absorber of 0.5 mm wire radius would absorb about 6.4 times more water vapor than one of same size but with 5mm tube radius. However, the overall performance has almost no effect on the system heat ratio.

**Key words: Absorption, Refrigeration, heat and mass transfer, falling film**

## 1 Introduction:

Vapor absorption refrigeration systems, VAS, differs from the vapor compression refrigeration systems, VCS, by the means of extracting the refrigerant vapor from the evaporator. In absorption refrigeration systems, the absorber-generator replaces the compressor in VCS, Gosney (1982). A strong solution enters the absorber where it absorbs vapor coming from the evaporator, during which heat is released. The lower is the absorbent temperature, the higher the affinity of the absorbent to vapor. This makes cooling of the absorbent becomes important.

Therefore the description of the process requires the simultaneous effects of heat and mass transfer, Griger'eva and Nakoryakov (1977), Nakoryakov and Griger'eva (1980), Van der Wekken and Wassenar (1988), and Karami and Farhanieh (2009).To maximize the refrigeration capacity in vapor absorption refrigeration systems, the rate of vapor extracted from the evaporator must be maximized. This is achieved by changing the absorbent concentration as it passes through the absorber as large as possible. To achieve this goal, the absorbent must be cooled and the contact areas between the vapor and absorbent and the coolant and absorbent must be as large as possible. Such requirement can be achieved by various absorber arrangements. But the falling film type arrangement is finding increasing favor as indicated by Burdakove et al (11980) and Ramshaw and Winnington (1989). Generally, most absorbers are constructed using a bank of horizontal tubes as indicated by Auracher et (2008). Strong absorbent falls down due to gravity forming a film around the outer surface of the tubes, where it absorbs vapor and release heat that must be transferred to the coolant that passes though the inside of tubes. The performance of a falling film over a vertical tube and flat surface in vapor absorption refrigeration systems is being used quite often by researchers, Kim and Kamg (1995), Tsem et al (2001), and Bo et al (2011). The present study is a theoretical investigation of the performance of an absorber of 0.5 mm multi-wires radius. The cooling of the absorbent will take place by conduction through the wire that is assumed to be cooled on one end or both ends.

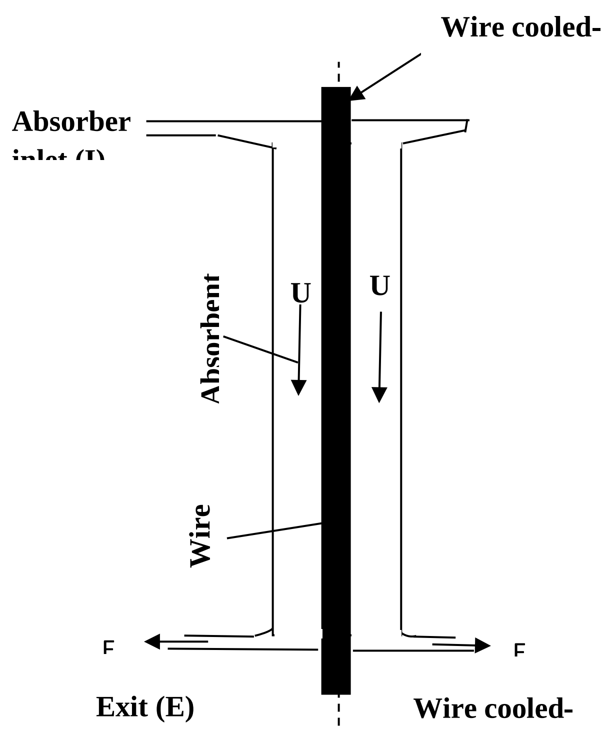


Fig.1. is schematic diagram of falling film absorber along a wire.

## 2 Theory:

The system geometry is shown in Fig. 1. The strong absorbent from the generator enters the absorber at "I" and return to the generator at "E". The analysis covers the fully developed smooth laminar flow in the absorbent. There is no general agreement among researchers at what Reynolds number the falling films appears to be smooth. Ruckenstein and Berbente, (1965), and Hirshburg and Florschuetz (1982) reported a smooth film at Re < 40 where as Hounkanlin and Dumargue (1986) observed smooth film at Re <= 80. Saber (1993) compared the wavy film to smooth one and showed that the enhancement of mass transfer at Reynolds number of 400 drops significantly along the film. But reducing Reynolds number below a critical value, the falling film breaks up and causes dry spots on the tube surface. Zhang et al (2010) investigated experimentally the flow pattern and liquid film break-up in single microchannel falling film micro-reactors. They measured the minimum wetting flow rate (MWF) with different geometries. They found that MWF increases with increasing the depth or width of the micro-channel. Kim and Lee (2003) conducted experimental work on falling film over horizontal tube absorber. The absorber consists of six tubes arranged in rows. They reported a minimum Reynolds number of 75 for full wettability of surface. More research on the critical Reynolds number is required. However, in the current study the theoretical model will be solved assuming smooth film at Re = 80. Further assumptions are:

- The vapor is single phase
- One component of the absorbent is non-volatile
- The absorbents are Newtonian and physical properties are constant with respect to temperature and concentration.
- The rate of vapor absorbed is small compared to the absorbent flow rate. Therefore the absorbent flow rate is constant and therefore its film thickness and mean velocity are also constant.

Under the above mentioned conditions the governing equations in cylindrical coordinates are:
The velocity profile in the absorbent falling film is

$$u = \frac{g r_o^2}{2\upsilon}\left[(1+\varepsilon)^2 \ln\frac{r}{r_o} - 0.5\left(\left(\frac{r}{r_o}\right)^2 - 1\right)\right] \tag{1}$$

Where the mean velocity is:

$$\bar{u} = \frac{g r_o^3}{4\upsilon(1+0.5\varepsilon)\delta} E_\varepsilon \tag{2}$$

And

$$E_\varepsilon = \left\{(1+\varepsilon)^4\left[\ln(1+\varepsilon) - 0.75\right] + (1+\varepsilon)^2 - 0.25\right\}$$

$\varepsilon$ is defined as $\delta/ ro$ and must be less than 1.0 because of the small curvature. The film thickness, $\delta$, and the dimensionless film thickness, $\varepsilon$ are derived in terms of Reynolds number, Re, and Galileo number, Ga, and suggested by Sinkunas et al (2005) as

$$\varepsilon = 1.67\left(\sqrt{1 + 1.09(\mathrm{Re}/\mathrm{Ga})^{1/3}} - 1\right) \quad \text{and} \quad \delta = \varepsilon\, r_o. \tag{3}$$

The diffusion and energy equations are as follow

$$u\frac{\partial C}{\partial x} = D\left[\frac{1}{r}\frac{\partial C}{\partial r} + \frac{\partial^2 C}{\partial r^2}\right] \tag{4}$$

$$u\frac{\partial T}{\partial x} = \alpha\left[\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2}\right] \tag{5}$$

## 2.1 Boundary Conditions:

### 2.1.1 Vapor-Absorbent Interface:

Due to vapor pressure difference between the vapor and absorbent at the interface, the vapor condenses on the absorbent and consequently gives out heat. This heat diffuses into the bulk of the absorbent. The concentration and temperature tends to be in equilibrium at the interface and so they are related by the following equations,

$$\frac{\partial T}{\partial r} = \frac{\dot{M}_v}{k}\delta h \tag{6}$$

$$\delta h = h_v - \left[h + (1 - C)\frac{\partial h}{\partial C}\right] \tag{7}$$

$$\dot{M}_v = \frac{\rho D}{1 - C}\frac{\partial C}{\partial r} \tag{8}$$

The absorbent concentration and temperature are assumed to be in equilibrium at the interface at the operating vapor pressure,

$$T_i = f(C_i) \tag{9}$$

The actual equilibrium relationship between the absorbent concentration and temperature within the practical application is found by Ibrahim and Vinnicombe (1993) to be approximately linear,

$$T_i = a + bC_i \tag{10}$$

### 2.1.2 Cold-wire-Absorbent:

Reducing the absorbent temperature will enhance the absorption process of vapor. The heat given out at the vapor-absorbent interface diffuses to the bulk of the absorbent. Therefore, the absorbent must be cooled by external means, otherwise it will become warm to absorb vapor at the required pressure. In the current study, the wire, over which the absorbent is falling, is cooled at one end or both ends. This is expected to conduct the heat from the absorbent. The equations describing this process are as follows;

$$\left.\frac{\partial C}{\partial r}\right|_{r=r_o} = 0 \tag{11}$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=r_o} = \left(\frac{k_c}{k_a}\right)\frac{r_o}{2}\frac{d^2T_c}{dx^2} \tag{12}$$

Due to the equilibrium state at the vapor-absorbent interface, a sudden change in absorbent conditions at absorber inlet is most likely to occur and a point of singularity will therefore exist and precaution should be taken while solving the problem. By using the dimensionless parameters the governing equations will be

$$X = \frac{x\alpha}{\bar{u}\delta^2}; \qquad \gamma = \frac{C - C_{in}}{C_e - C_{in}}; \qquad \theta = \frac{T - T_{in}}{T_e - T_{in}}; \qquad R = \frac{r - r_o}{\delta};$$

$$L_e = \frac{D}{\alpha}$$

Where Tin and Cin are the absorbent conditions at the inlet, Ce is the equilibrium concentration at Tin and Te is the equilibrium temperature at Cin, the governing equations can be written in the following dimensionless form

$$U = \frac{u}{\bar{u}} = \frac{(2+\varepsilon)\varepsilon}{E_\varepsilon}\left[(1+\varepsilon)^2 \ln\frac{r}{r_o} - 0.5\left(\left(\frac{r}{r_o}\right)^2 - 1\right)\right] \tag{13}$$

$$U\frac{\partial\gamma}{\partial X} = L_e\left[\frac{1}{R+1/\varepsilon}\frac{\partial\gamma}{\partial R} + \frac{\partial^2\gamma}{\partial R^2}\right] \tag{14}$$

$$U\frac{\partial\theta}{\partial X} = \frac{1}{R+1/\varepsilon}\frac{\partial\theta}{\partial R} + \frac{\partial^2\theta}{\partial R^2} \tag{15}$$

## 2.2 Dimensionless Boundary Conditions:

### 2.2.1 Vapor-Absorbent Interface (R = 1):

$$\frac{\partial\theta}{\partial R} = H\frac{\partial\gamma}{\partial R} \tag{16}$$

$$H = \frac{\rho D}{(1 - C_{in})k} \frac{C_e - C_{in}}{T_e - T_{in}} \delta h \tag{17}$$

The dimensionless absorbent concentration and temperature at the interface at the operating vapor pressure

$$\theta + \gamma = 1 \tag{18}$$

**2.2.2 Cold-wire-Absorbent (R = 0):**

$$\left.\frac{\partial \gamma}{\partial R}\right|_{R=0} = 0 \tag{19}$$

$$\left.\frac{\partial \theta}{\partial R}\right|_{R=0} = - C_f \frac{d^2\theta_c}{dX^2} \tag{20}$$

Where the Cf is the cooling factor

$$C_f = \frac{\varepsilon}{8}(k_c)/(k_a) \frac{1}{(R_e P_r)^2} \tag{21}$$

If both ends are cooled, the wire temperature will have a maximum temperature between wire ends, i.e. the temperature increases until it reaches a maximum in the X-direction and then decreases again. For bottom cooled wire end, the temperature decreases in the X-direction.

## 3 Solution:

Explicit finite difference method-Matlab codes (Self written program) have been used to solve the above governing equations. However, it was found that because of the singularity within vapor-absorbent interface at entry and small Lewis number, the finite difference method is mesh size dependent and requires a distance to converges to the true solution. The numerical domain is divided into N and M nodes in the axial and transverse coordinates. The grid size $\Delta X$ is related to the grid size $\Delta R$ by the stability criteria for the explicit finite difference method and calculated for the selected M-nodes. The grid size was investigated by running the program with M = 80, 120, 160 and 300. It was found that, the discrepancy of average concentration produced with M = 80 and M = 300, for LitBr (Le = 0.0083 and H = 0.0934), was less than 1%, for Le = 0.001 was less than 3.2% and for Le = 0.0001, was less than 35%. Therefore, M = 80 was chosen to perform all calculation except for Le = 0.0001, M = 120 was applied to ensure accuracy. Ibrahim and Vinnicombe (1993) showed that the linear relation between concentration and temperature at the vapor-absorbent interface may be well used with insignificantly small error in particular for dimensionless length of X up to 5.

In vertical absorber, the absorbent forms a falling film either on the inside of the tube and the cooling medium flows on the outside Tsem et al (2001), or on the outside surface of the tube and cooling medium flows through the inside, Saber (1993). The size of the tube with the absorbent flowing on the inside should be large enough to accommodate the water vapor extracted from the evaporator with minimum pressure drop. For the case where the absorbent flows on the outside, the size of the vertical tube is also important in terms of contact area between vapor and absorbent, and space occupied. Although large tubes provide large contact (preferred), it occupies larger space (un-preferred). In practice reducing the tube radius is limited by having a slow to non-flow of cooling medium on the inside surface of the tube. To benefit from smallest possible size of the tube, the simultaneous cooling must be achieved by a different way, probably by conduction as will be investigated in this study.

The results obtained and discussed in section-5 "results and discussion", on the other hand, are produced at Cf = 1, 10, 100. For Cf < 1.0, there was no cooling and results were not acceptable. For a practical absorber using LitBr-Water absorbent the Cf is less than 1. This indicates that such design for LitBr-Water absorbent is infeasible.

## 4 Comparison previous work:

The current study has been compared with Karami & Farhanieh (2009) under similar conditions as shown in table 1. Karami & Farhanieh (2009) have studied numerically the absorption process of water vapor into a falling film along a vertical plate. The deviation varies between 1.8% and 5.98%. The deviation increases along the absorber length, but it is still.

Table 1: Concentration (water mass concentration in absorbent)

| Position, x [m] | Karami & Farhanieh (2009) | Current Study | Deviation [%] |
|---|---|---|---|
| 0.06 | 0.423 | 0.430642 | 1.806559 |
| 0.12 | 0.429 | 0.441088 | 2.81763 |
| 0.18 | 0.434 | 0.446443 | 2.866999 |
| 0.3 | 0.438 | 0.453617 | 3.565575 |
| 0.48 | 0.4433 | 0.462084 | 4.237211 |
| 0.6 | 0.446 | 0.466874 | 4.680301 |
| 0.9 | 0.4508 | 0.476262 | 5.648166 |
| 1.2 | 0.457 | 0.484245 | 5.961808 |

## 5 Results and Discussion:

The concept of effectiveness to describe the performance of heat absorber is a useful tool in heat exchanger analysis and so it has been adopted in absorber analysis by Ibrahim (1991) and Saber (1993). The effectivenesses applied in the present study are the mass and cooling effectiveness. The mass effectiveness seems to be more appropriate and descriptive of an absorber, since it relates the actual vapor mass flow rates absorbed to the maximum vapor mass flow rate absorbed. Since the absorber is neither a heat exchanger nor a condenser, but somewhere in between, the heat effectiveness was based on the coolant although the thermal capacity of absorbent is smaller than the coolant thermal capacity, Ibrahim (1991) and Saber (1993).

The objective of an absorber is to enhance the absorption rate by removing the heat of absorption and possibly reducing the absorbent temperature, a cooling effectiveness is defined as the actual total energy (Latent and sensible) to be removed from the absorbent divided by the total energy that can be removed by an ideal absorber,

$$\varepsilon_c = \frac{(\dot{m}Cp)_a (T_{si} - T_{so}) + \dot{m}_v \delta h}{(\dot{m}Cp)_a (T_{si} - T_{cin}) + \dot{m}_{v,max} \delta h} \tag{22}$$

and the mass effectiveness is defined as the actual vapor flow rate absorbed divided by that maximum vapor flow arte obtained by an ideal absorber where the exit concentration is at equilibrium at cooling medium temperature.

$$\varepsilon_m = \frac{\dot{m}_v}{\dot{m}_{v,max}} \tag{23}$$

Using dimensionless groups, the cooling effectiveness is then

$$\varepsilon_c = \frac{H_f / \lambda - \theta_{a,o}}{H_f / \lambda_{max} - \theta_{c,in}} \tag{24}$$

Where

$$H_f = (H / Le)\lambda_r$$

and λ and λmax are the circulation factors of an actual absorber and ideal absorber where the concentration at the ideal absorber exit is at equilibrium with inlet coolant temperature respectively.

$$\lambda_r = (1 - C_{in}) / (C_e - C_{in})$$

$$\lambda = \left(\lambda_r / \gamma_o\right) - 1$$

$$\lambda_{max} = \left[\lambda_r / (1 - \theta_{cin})\right] - 1$$

And the mass effectiveness may be expressed in terms of circulation factor as

$$\varepsilon_m = \frac{\dot{m}_v}{\dot{m}_{v,max}} = \frac{\dot{m}_{a,in}/\lambda}{\dot{m}_{a,in}/\lambda_{max}} = \frac{\lambda_{max}}{\lambda} \tag{25}$$

Therefore the cooling effectiveness becomes

$$\varepsilon_c = \frac{H_f - \theta_{a,o}\lambda}{H_f - \theta_{c,in}\lambda_{max}}\varepsilon_m \tag{26}$$

The limit of the cooling effectiveness is depending on the Hf value whose limit is in turn depending on the ratio of (H/Le) λr. But λr ≈ 10, therefore Hf may vary between λr (at H = 0.01 and Le = 0.01) and 104 (at H = 0.1 and Le = 0.0001) and so εc may vary between θa,o/θc,in and εm.

From the design perspective, the cooling effectiveness contains two unknowns, the actual absorbent exit temperature and exit concentration. Therefore, a second design parameter must be specified prior to use of the cooling effectiveness. The second parameter can be the circulation factor, which provides the exit concentration. However, the usefulness of the cooling effectiveness that it provides information about the absorbent exit conditions, rather than the cooling medium conditions.

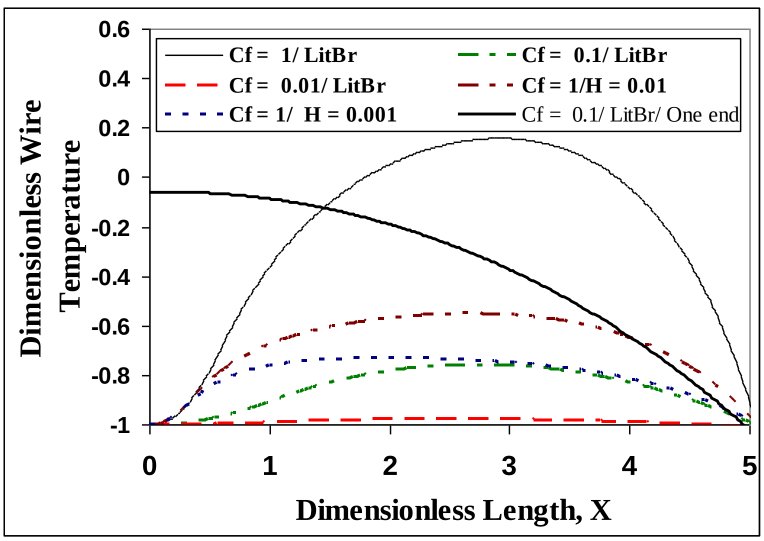


Fig. 2. Dimensionless wire temperature along the absorber length, X.
θc,in = -1, θc,b = -1,Re = 80, ro = 0.5 mm, LitBr-Water (H = 0.0934 and Le = 0.0083).

In Practice, the wire may be cooled on both ends, such that the latent and sensible heat of absorbent is removed by conduction. The cooling medium to be used to cool the wire ends must flow under atmospheric pressure and not to mix with absorbent, which flows under vacuum. Therefore the wire end on the absorbent entry must be extended to the outside of the inlet absorbent distribution system. Designing such a system is possible, but this might cool the absorbent at the distributor exit below the crystallization point and causes blocking of the distributor system. Crystallization problem is an important criterion when it comes to the distributor system design and must be avoided. It is also possible to cool only the bottom end of the wire. In the present work, results will be shown for both ways of cooling. Fig. 2 shows that for an absorber dimensionless length of 5 the wire temperatures at cooling factor, Cf, of 1, 10, 100 with wire temperature of -1 at both ends rises from -1 to a maximum and then drops back to -1. The maximum value depends on the cooling factor the cooling factor. With increasing cooling factor, the maximum drops and at a sufficiently large cooling factor, the maximum disappear. However, with bottom end cooled wire, the wire temperature does not go through a maximum as shown in Fig. 2.

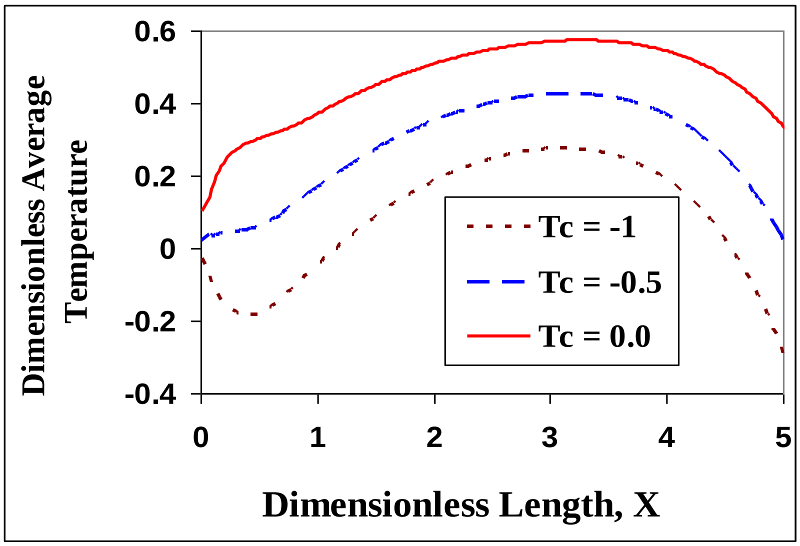


Fig.3. shows the behavior of the absorbent average temperature along the tube length at various wire end temperatures. Re = 80, ro = 0.5 mm, Cf = 1, LitBr-Water (H = 0.0934 and Le = 0.0083).

Fig.3 shows the effect of cooling temperature on the average absorbent temperature. For cooling temperature of 0.5 and 0, the average absorbent temperature went through a maximum before it fell to the exit temperature. The increase in average temperature had no effect on the average concentration near the inlet. This may be due the fact that the water vapor did not penetrate deep in the falling film yet. But further down from the inlet, it seemed to have reduced the slop of the average concentration as shown in Fig.4. It can also be seen from Fig. 3 that for cooling temperature -1, the average temperature went through a minimum near the inlet then it increased to a maximum before began to fall to its exit temperature. As expected, the increase in cooling temperature reduced the average concentration.

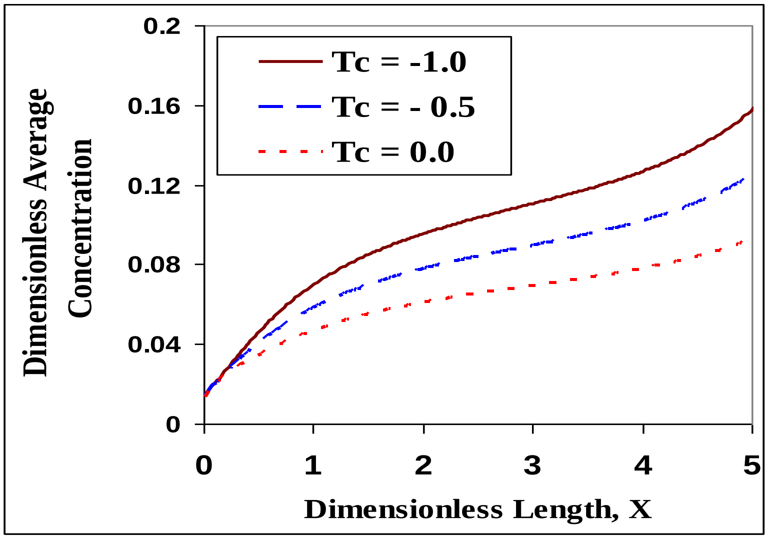


Fig. 4: shows the behavior of the absorbent average concentration along the tube length at various wire end temperatures. Re = 80, ro = 0.5 mm, Cf = 1, LitBr-Water (H = 0.0934 and Le = 0.0083)

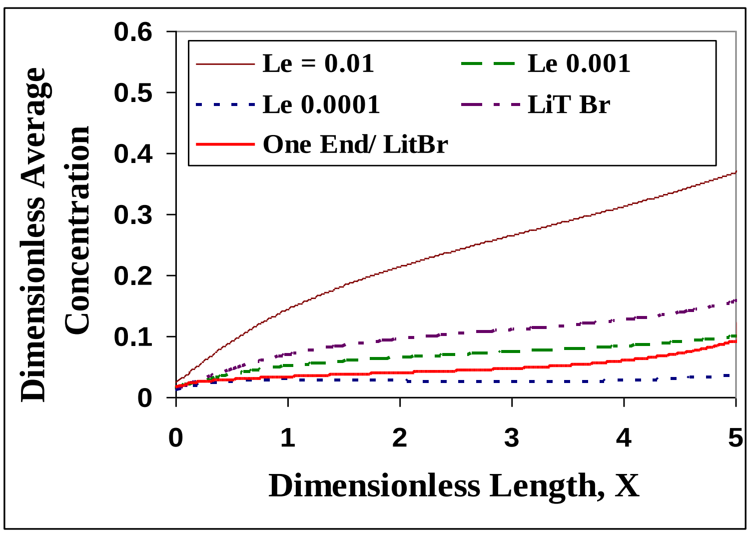


Fig.5. the effect of Le and LitBr-Water for both end and one end coled wire on the absorbent average concentration. θc,in = -1, θc,b = -1, Re = 80, ro = 0.5 mm, Cf = 1, LitBr-Water (H = 0.0934 and Le = 0.0083)

Fig. 5 compares the change of concentration along the X-axis for Le = 0.01, 0.001, 0.0001 with H = 0.01, LitBr-Water for cooling of both wire ends and one end. The average concentration change increases with increasing Lewis number. So it is highest for Le = 0.01. Results for LiBr-Water are produced with the wire cooled on both ends and on one end. The average concentration change with cooling of wire on both ends is insignificantly higher than that with cooling of wire on one end. But using wire cooled on one end is still producing significant concentration change along the X-axis.

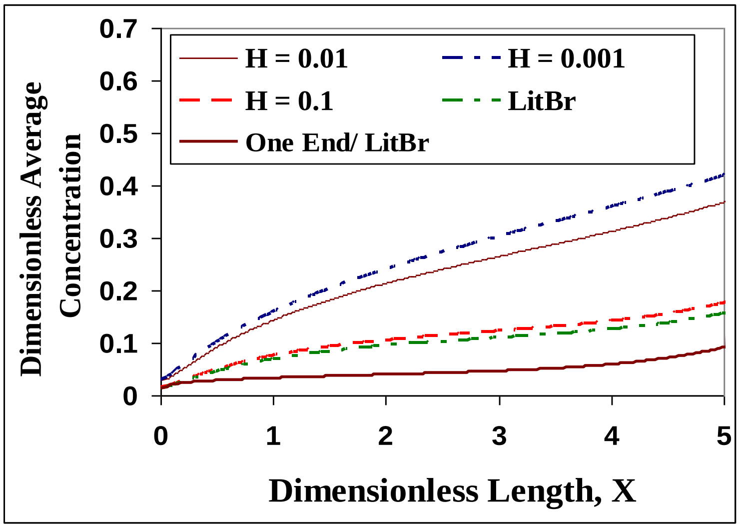


Fig. 6. the effect of H and LitBr-Water for both end coled wire on the absorbent average concentration. θc,in = -1, θc,b = -1, Re = 80, ro = 0.5 mm, Cf = 1, LitBr-Water (H = 0.0934 and Le = 0.0083)

Fig. 6 compares the change of concentration along the X-axis for H = 0.1, 0.01, 0.001 with Le = 0.01 and LitBr-Water. As expected, the higher the heat of absorption, the slower the change in average concentration. The change in average concentration for LitBr-Water is lowest. This is obviously due to the fact that Lewis number (for LiBr-Water, = 0.0083 < 0.01) has reduced the absorption process more than the heat of absorption (for LiBr-Water = 0.0934 < 0.1) has improved.

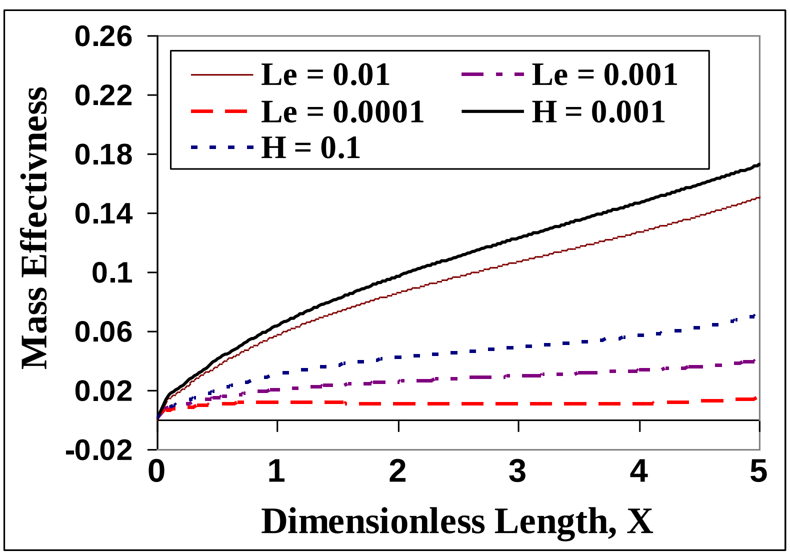


Fig.7. The mass effectiveness is plotted versus the absorber length at different Lewis numbers and heat of absorption. θc,in = -1, θc,b = -1, Re = 80, ro = 0.5 mm, Cf = 350 E3, LitBr-Water (H = 0.0934 and Le = 0.0083).

Fig.7 is presenting the effect of the Lewis number and heat of absorption on the mass effectiveness and Fig.8 shows the cooling effectiveness behavior along the dimensionless length with respect of Lewis number and heat of absorption. At X = 5 and from Fig.7 it can be seen that by reducing the heat of absorption, H from 0.1 to 0.01, the mass effectiveness, εm, increases by about 53%, but reducing it from 0.01 to 0.001, the increase in εm is only about 12.7%. Reducing the Le by 10 folds, the εm drops by about 74% and by reducing by 100 folds, the εm drops by about 92%. On the contrary, reducing the heat of absorption increases the cooling effectiveness, εc, whereas reducing the Lewis number, reduces εc. This is due to the fact that reducing the Le, increases the Hf value in equation (26), so that εc will drop towards εm.

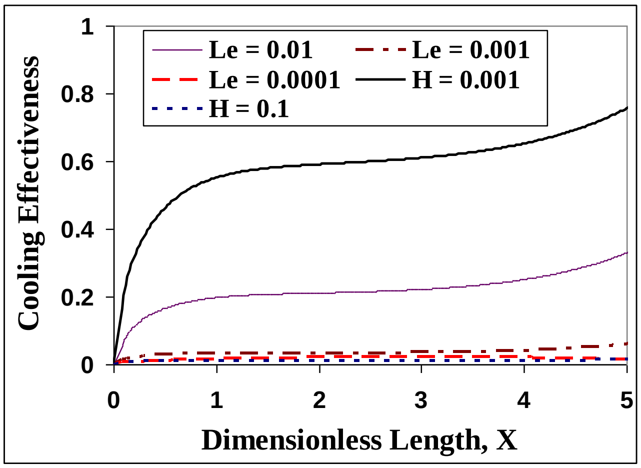


Fig.8. The cooling effectiveness is plotted versus the absorber length at different Lewis numbers and heat of absorption. θc,in = -1, θc,b = -1, Re = 80, ro = 0.5 mm, Cf = 1, LitBr-Water (H = 0.0934 and Le = 0.0083

In the current study, an overall absorber performance, Eff, is defined as the actual vapor flow rate absorbed by multi tube absorber of one unit space area divided by that maximum vapor flow arte obtained by one-tube absorber of one unit space area where the exit concentration is at equilibrium at cooling medium temperature. This will take into account the total contact area of all absorber tubes that occupy one unit space area. i.e. the number of tubes forming the absorber of one unit space area decreases with increasing the tube radius. The overall absorber performance, Eff, is

$$E_{ff} = \frac{\dot{m}_{v,t}}{\dot{m}_{v,smx}} \tag{27}$$

Where $\dot{m}_{v,t}$ is the actual total vapor mass flow rate and $\dot{m}_{v,smx}$ is the vapor flow rate that is obtained from an absorber of a single tube that occupies one unite space area where the absorbent leaves the absorber with an equilibrium concentration at the inlet coolant temperature.

With $\dot{m}_{v,t}$ = 2 π ro Γ No/λ, $\dot{m}_{v,smx}$ = 2 π ro,s Γ/λmax and No = π ro,s2 /π ro2 , the overall performance becomes

$$E_{ff} = \frac{r_{o,s}\lambda_{max}}{r_o\lambda} = \frac{r_{o,s}}{r_o}\varepsilon_m \tag{28}$$

where for one single tube that occupy 1 m2, ro,s = 564.2 mm. This is the reference radius taken to calculate the overall performance in this work.

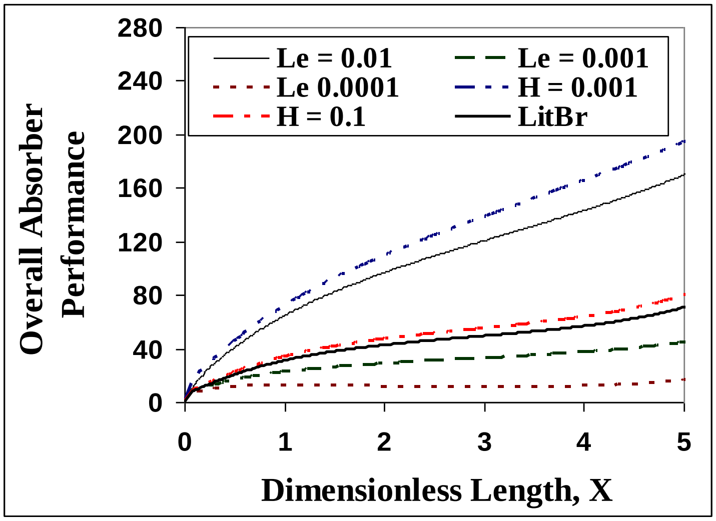


Fig. 9 the overall performance is plotted against the absorber length at different Lewis numbers and heat of absorption. θc,in = -1, θc,b = -1, Re = 80, ro = 0.5 mm, Cf = 1 , LitBr-Water (H = 0.0934 and Le = 0.0083

In Fig.9 the overall performance, Eff, is plotted along the X-axis at different Lewis number and heat of absorption. The behavior of the Eff is similar to the εm shown in Fig. 7. The overall performance for different tube radii (40mm, 20mm, 5mm) with water cooling at Cr = 100 applying the cooling boundary condition as given in equation 29 (Ibrahim (1991), page 76).

$$\left.\frac{\partial\theta}{\partial R}\right|_{R=0} = -\,Cr\,\frac{d\theta_c}{dX} \tag{29}$$

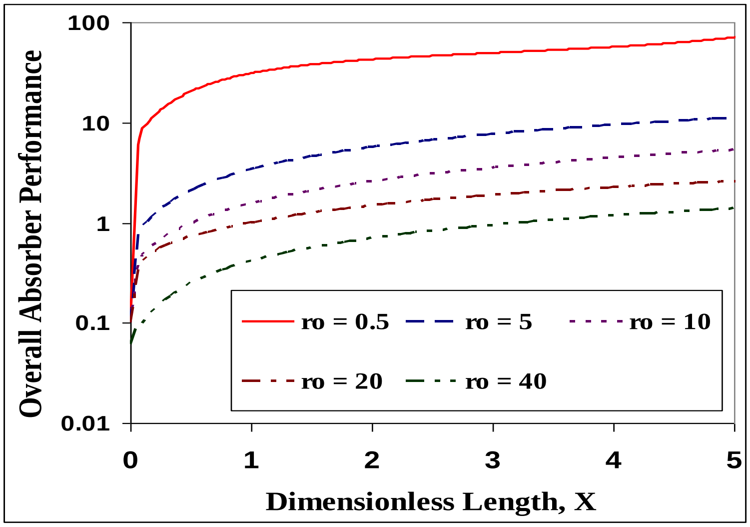


Fig.10. The overall performance is plotted against the absorber length at different tube radii. θc,in = -1, θc,b = -1, Re = 80, ro = 0.5 mm, Cf = 1, LitBr-Water (H = 0.0934 and Le = 0.008

Fig. 10 shows the effect of tube radius on the overall performance. A logarithmic scale is used present the vertical axis. This due to the large range from ro = 0.5mm to ro = 100 mm. The overall performance increases with decreasing the radius. At dimensionless length of 5, Eff is 11.22 at ro = 5 mm and 71.55 at ro = 0.5 mm i.e. 6.4 times higher. This means that with 0.5 mm radius of multi-wires absorber will absorb water vapor about 6 times more than that of 5mm radius of multi-tube absorber.

## 6 Conclusion

Results were presented in terms of Lewis number, heat of absorption and cooling factor. The effect of wire one end cooled is insignificantly small. With reducing the end wire temperature, the average concentration increase. The cooling effectiveness increases with reducing the heat of absorption and with increasing Lewis number. The mass effectiveness increases with increasing the Lewis number and reduces with increasing heat of absorption. It has been shown that the overall performance of a multi-vertical tube absorber increases with reducing the tube radius, i.e. for the same absorber size, the mass flow rate of vapor increases and so does the cooling capacity in the evaporator. The overall performance of 0.5mm wire (heat transferred by conduction) is 10 times greater than that of 5mm tube radius (water cooled). However, using wire to cool the LitBr-water absorbent is not feasible.

## References


Auracher, H., Wohlfeil, A. and Ziegler, F. (2008). A simple physical model for steam absorption into a falling film of aqueous lithium bromide solution on a horizontal tube, Heat Mass Transfer, 44, 1529-1536.

Bo, S., Ma, X. and Chen, H. (2011). Numerical simulation on vapor absorption by wavy lithium bromide aqueous solution films, Heat Mass Transfer, 47, 1611-1619 17.

Burdakov, A. P., Bufetov, N. S. and Derity N. P. (1980). A. R. Durokhov and V. I. Kazakov, Experimental study of the absorption of water vapor by thin films of aqueous LitBr, Heat Tansfer-Sov. Res. 12, 118-123.

Gosney, W. B. (1982). Principles of Refrigeration, Cambridge University Press, Cambridge.

Griger'eva N. I., and Nakoryakov, V. E. 1977, Exact solution of combined heat and mass transfer during film absorption, Inzh.-fiz. Zh. 33, 893-898.

Gylys, S. J. and Kiela, A., (2005). Analysis of laminar liquid film flowing down a vertical surface, 4th international Conf. ob CFD in the Oil and Gas, Metallurgical and Process Industries, SINTEE/ NTNU Trondheim, Norway, 6-8 June.

Hirshburg R. I. and Florschuetz L.W. (1982). Laminar wavy flow: Part I hydrodynamics, Trans. Am. Soc. Mech. Engrs. 4, 452.

Hounkalin M. A. and Doumargue, P. (1986). Statistical characteristics of intermittent liquid film flow, Int. J. Heat Mass Transfer, 7, 3, 223-230.

Ibrahim, G. A. Vinnicombe, G. A. (1993). A hybrid method to analyze the performance of falling film absorbers, In. J. Heat Mass Transfer, 36, 5, 1383-1390.

Ibrahim, G. A. (1991). An investigation into falling film absorbers for refrigeration systems, PhD Thesis, King's College, University of London.

Karami, S. and Farhanieh, B. (2009). A numerical study on the absorption of water vapor into a film of aqueous LitBr Falling along a vertical plate, Heat Mass Transfer, 46, 197-207.
Kim, B. J. and Kamg, I. S. 1995, absorption of water vapor into wavy-laminar falling film of aqueous lithium-bromide, KSME J. 9, 1, 115-122.

Kim, B. and Lee, C. (2003). Non-absorbable gas on heat and mass transfer in falling film absorption, KSME Int. J 17, 4, 581-589.

Nakoryakov, V. E. and Griger'eva, N. I. (1980). Calculation of heat and mass transfer in non-isothermal absorption on the initial portion of a down flowing film, Teor. Osnory Khimish. Tekh. 14, 483-488.

Ramshaw, C. and Winnington,T. L. (1989). An intensified absorption heat pump, Proc. Inst. Refrig. 2.1-2.6.

Ruckenstein, E. and Berbente, C. (1965). Mass trabsfer in wavy flow, Chem.Eng. Sci.20,795-801

Saber, H. (1993). Heat and mass transfer processes in absorption systems, PhD Thesis, Dept. of Mech. Eng., Kings College- University of London.

Tsem, I. Lin, I. P. and Chou, S. F. (2001). Heat and mass transfer in the vertical twin-parallel-tube absorber-evaporator unit, J Chinese Inst. Eng., 24, 5, 581-593.

Van Der Wekken, B. J. C. and Wassenar, R. H. (1988). Simultaneous heat and mass transfer accompanying absorption laminar flow over a cooled wall, Inter. J. Refrig. 11, 70-77.

Zhang, H., Yue, J., Chen, G. and Yuan, Q. (2010). Flow pattern of liquid film in single-channel falling film micro-reactors, chemical engineering journal, 163, 126-132.

## List of symbols

| | | |
|---|---|---|
| a | Constant in equation (10) | |
| b | Constant in equation (10) | |
| C | Concentration | |
| Cf | cooling factor | |
| CP | Specific heat | [J kg-1 K-1] |
| Cr | Heat capacity ratio $= (\dot{m}\,Cp)_c / (\dot{m}\,Cp)_a$ | |
| D | Diffusion coefficient | [m2 s-1] |
| Eff | Absorber overall performance | |
| Ga | Galileo number (g r3/ν2) | |
| g | Gravitational constant | [ms-2] |
| h | Enthalpy | [J kg-1] |
| δh | Heat of absorption | [Jkg-1] |
| H | Dimensionless heat of absorption | |
| Hf | Heat factor (H/Le)λr | |
| k | Thermal conductivity | [W m-1 K-1] |
| Le | Lewis number | |
| $\dot{m}$ | mass flow rate | [kg $s^{-1}$] |
| $\dot{M}_v$ | vapor mass flux | [kg $m^{-2}s^{-1}$] |
| $\dot{m}_v$ | vapormassflow rate | [kg $s^{-1}$] |
| No | Number of tubes | |
| Pr | Prandtl number | |
| Re | Reynolds number (4Γ/ν) | |
| r | Radial coordinate | [m] |
| ro | Tube or wire radius | [m] |
| R | Dimensionless radial coordinate | |
| T | Temperature | [°C] |
| u | Velocity | [$ms^{-1}$] |
| $\bar{u}$ | Mean velocity | [m $s^{-1}$] |
| U | Dimensionless velocity | |
| x | Coordinate in flow direction | [m] |
| X | Dimensionless coordinate in flow direction | |

**Greek symbols**

| | | |
|---|---|---|
| Γ | Mass flow rate per wetted perimeter | [kg $m^{-1}$ $s^{-1}$] |
| α | Thermal diffusivity (k/ρ Cp) | |
| γ | Dimensionless concentration | |
| δ | Film thickness | [m] |
| ε | Film thickness ratio (δ/ro) | |
| εc | Cooling effectiveness | |
| εm | Mass effectiveness | |
| λr | Concentration factor (1 - Cin)/ (Ce - Cin) | |
| λ | Circulation factor (λr/γo – 1) | |
| θ | Dimensionless temperature | |
| ρ | Density | [kg $m^{-3}$] |
| ν | Kinematic viscosity | [$m^2$ $s^{-1}$] |

**Subscripts**

| | |
|---|---|
| a | absorbent |
| av | average |
| b | bottom end |
| c | wire |
| i | Absorbent-vapor interface |
| in | inlet |
| max | maximum state |
| s | single tube |
| smx | single tube maximum state |
| o | exit |
| t | total |
| v | vapor |
| w | absorbent at the wall |