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Numerical Simulation of Solution Droplets and Falling Films in Horizontal Tube Absorbers

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Abstract : This paper presents a numerical simulation of the behavior of the LiBr solution droplets and falling films in horizontal tube banks of absorber. The model developed here accounts for the details of the droplets formation and impact process for absorption on horizontal tubes including the heat transfer from solution film to the tube wall. Especially, the characteristic of unsteady behavior of solution flow has been investigated. Flow visualization studies shown that the solution droplets and falling films have some of the complex characteristics. It is found that, with the numerical conditions similar to the operating condition of an actual absorption chiller/heater, the outlet solution temperature and heat flux from solution film to the tube wall have a stable periodic behavior with time. The solution droplets and falling films in horizontal tube banks of absorber is a periodic unsteady flow. The results from this model are compared with previous experimental observation taken with a high-speed digital video camera and shown good agreement.

Key words : Absorption chiller/heater, Tube absorber, Droplet, Falling film, Heat transfer, Visualization

Nomenclature

C_p : specific heat at constant pressure, J/kgK
k : thermal conductivity, W/mK
p : pressure, Pa
T : temperature, K
t : time, s
v : velocity, m/s
x : streamwise displacement, m
y : crosswise displacement, m

Greek letters

α : volume fraction, m^3/m^3
μ : dynamic viscosity, kg/ms

Subscripts

in : inlet
out : outlet
x : component in x direction
y : component in y direction

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1. Introduction

Absorption refrigeration, heat pump and heat transformer systems are becoming increasingly attractive because they can not only utilize the low temperature heat source to drive so that the solar energy, geological heat and low temperature waste heat discharged from various industrial processes can be possibly used, but they also completely differ from refrigeration systems employing CFCs as refrigerants that cause disastrous damage to our environment. The absorber in any absorption machine is a key component and its characteristics have significant effects on overall efficiency of absorption machines. In a horizontal tube absorber, absorbent strong solution is dispensed on the outside of the top row of tubes and falls as films around the tubes and as droplets between the tubes by the force of gravity while absorbing surrounding refrigerant vapor that enters from the evaporator, the heat of absorption is transferred to coolant flowing through the tubes.

The role of droplets in horizontal tube absorbers, in particular those employing the working fluid Lithium Bromide solution, has recently been highlighted in the literature. Nomura et al.[1] measured the temperature of the falling liquid absorbent in a horizontal tube absorber both on and between the tubes. Their results suggests that direct absorption onto the hanging droplets is a significant part of the total absorption process. Jeong et al.[2] developed a model that also accounts for absorption on the film, forming droplets, and falling droplets separately. Their results predict that direct absorption on the forming droplets may account for up to 50% or more of the total absorption. Killion et al.[3] developed an image analysis process to quantify the surface area and volume of droplets during their evolution in the region between the tubes. The results showed that although the satellite droplets may have a small total volume and surface area, they may still account for a significant fraction of the overall absorption. Several other noteworthy models of falling film absorption on horizontal tube absorbers can also be found in the literature[4],[5], however, all of these models share several simplifying assumptions that limit their usefulness: the film is assumed to be smooth and evenly distributed along the tubes. The droplet mode of flow between successive tubes is completely ignored.

The techniques for modeling droplet formation and impact have been studied for hundreds of years. Work in this field continues today aided by the advent of high performance computers and high speed, high resolution video cameras. A recent review by Eggers[6] provides an excellent summary of many modern mathematical, experimental, and computation methods utilized to better understand the details of the droplet behavior. It is important to note that the impact of droplets in the case of horizontal tubes and falling films has not received a great deal of attention.

In modeling of two phase flow with a free interface, due to the complexity of the problem and the ever increasing computation speed of computers, most recent attempts to mathematically analyze droplet formation have relied heavily on numerical techniques. Some literatures provided a review of several of these techniques. The volume-of-fluid (VOF) technique has proven to be one of the most effective, generally applicable techniques. The implementation of the VOF method is significant and growing rapidly. However, the apply VOF techniques to the modeling the formation of droplets and falling film in horizontal tube including heat transfer from liquid film to tube wall has been lacked.

In this paper, a model of solution droplets and falling films in horizontal tube banks of absorber has been developed. The model accounts for the details of the droplet formation and impact process for absorption on horizontal tubes including the heat transfer from solution film to the tube wall which has largely been ignored in previous studies. Especially, the characteristic of unsteady behavior of solution flow has been investigated. The results from this model are compared with pervious experimental observations taken with a high speed digital video camera.

2. Analysis model of solution pendant droplets and falling films

2.1 Analysis model and assumptions

In the horizontal tube absorber, the strong LiBr solution film is distributed by upper tray through the tray hole and flows down over tube surfaces as films around the tubes and as droplets between tubes. The film solution is in contact with water vapor which comes from evaporator. As water vapor is higher than the partial pressure of liquid water in solution, the water vapor is absorbed into solution. The heat of absorption is transferred to coolant flowing through the tubes. The schematic of solution pendant droplets and falling films model inside horizontal tube absorber is shows in Fig. 1. Due to symmetry of the tube banks and the periodicity of the flow inherent in the tube banks geometry, only a portion of the geometry is modeled, with symmetry applied to the outer boundary. The inflow region is reduced to only 3 tubes which are the first and last tubes at solution inlet and outlet and one at any location of the tube column as shown in Fig. 2.

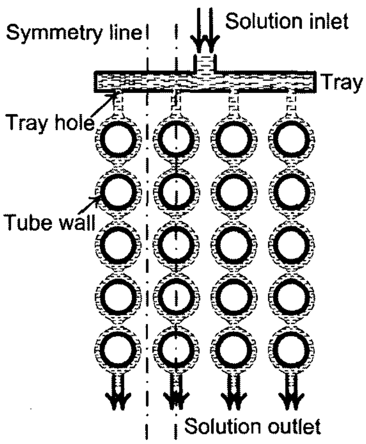

Fig. 1 Schematic of solution pendant droplets and falling films model

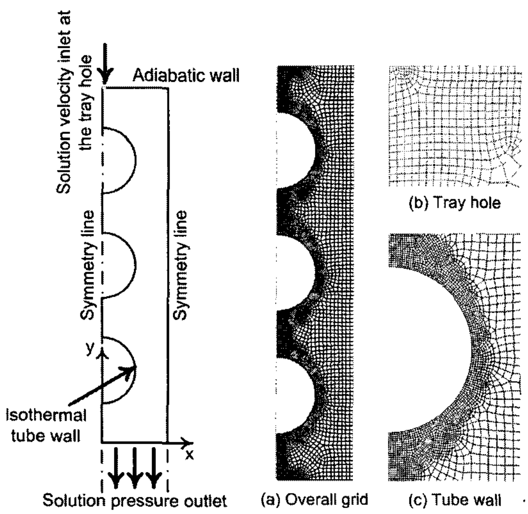

Fig. 2 Calculation domain with gird system

In formulating this model, the following assumptions have been made:

- The flow was assumed to be incompressible, Newtonian and laminar.
- The physical properties of the surrounding vapor were taken to be air since it is difficult to find the value of interfacial tension between LiBr solution and water vapor in literatures.
- The tube material is cooper and the wall temperature was assumed to be constant.

2.2 Governing equations, VOF method and boundary conditions

For 2-dimensional laminar flow with constant fluid and material properties, the governing equations for mass, momentum and energy in an unsteady state flow are given by:

Continuity:

$$\frac{\partial}{\partial x}(\rho v_x)+\frac{\partial}{\partial y}(\rho v_y)=0 \quad (1)$$

x-momentum:

$$\frac{\partial}{\partial t}(\rho v_x)+\frac{\partial}{\partial x}(\rho v_x v_x)+\frac{\partial}{\partial y}(\rho v_y v_x)= -\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial v_x}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v_x}{\partial y}\right)+g_x \quad (2a)$$

y-momentum:

$$\frac{\partial}{\partial t}(\rho v_y)+\frac{\partial}{\partial x}(\rho v_x v_y)+\frac{\partial}{\partial y}(\rho v_y v_y)= -\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\mu\frac{\partial v_y}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v_y}{\partial y}\right)+g_y \quad (2b)$$

Energy:

$$\rho C_p\frac{\partial T}{\partial t}+\frac{\partial}{\partial x}(\rho v_x C_p T)+\frac{\partial}{\partial y}(\rho v_y C_p T)= \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) \quad (3)$$

The concepts of VOF method have been described in [7]. The principle of the VOF method is that a single, scalar value in each computational cell is used to represent the fraction of that cell occupied by a particular phase. In cells containing only a single phase, the value will be either 1 or 0. In cells through which the phase interface passes, the value will be between 1 and 0 representing the volume fraction of the primary phase in that cell.

The boundary conditions are shown in Fig. 2. At the tube wall, no slip boundary condition ($v_x= v_y=0$) are imposed on the tube surfaces. The contact between the solution film and the tube wall is 0^o to ensure complete wetting in the simulation. The concepts of symmetry, adiabatic wall, velocity inlet, and pressure outlet boundary conditions have been described in[7].

2.3 Method of numerical analysis

A CFD software, Fluent[7], is used for the numerical analysis. The studied model shown in Fig. 2 is created and meshed by using Gambit software.

The fixed grids used in the present work were made up of quadrilateral cell which is known to be slightly more accurate when surface tension is an important force as is the case here, than triangles. The quadrilateral elements were finer near the tube walls, the tray hole and in regions where the two-phase interface was expected to pass, and coarser in regions where only the gas-phase was expected. The edge length varied from a minimum of 0.075mm and 0.2mm near the tray hole and tube walls to a maximum of 0.8mm. The face mesh contained 17,242 quadrilaterals. Then, the created model in Gambit software is exported to the Fluent software in which boundary conditions and material properties are defined. A segregated solution approach using the PISO algorithm, as implemented in Fluent[7], is used to link the pressure and velocity fields.

Table 1 Physical properties and parameters used in computation analysis

Parameters	Values
Tube length [m]	1
Diameter [m]	0.01588
Transverse pitch [m]	0.025408
Transverse pitch to diameter ratio	1.6
Diameter of tray hole [m]	0.0015
Wall temperature [°C]	32
Surrounding air temperature [°C]	32
Inlet solution temperature [°C]	47
Inlet solution concentration [wt%]	61
Solution film Reynolds number	30
Physical properties of air	
Density [kg/m^3]	1.1572
Dynamic viscosity [kg/ms]	1.8×10^{-5}
Specific heat [J/kg]	1010
Thermal conductivity [W/mK]	0.026489
Physical properties of LiBr solution	
Density [kg/m^3]	1772.8377
Dynamic viscosity [kg/ms]	0.0049331
Specific heat [J/kg]	1892
Thermal conductivity [W/mK]	0.4276
Surface tension [N/m]	0.085604

3. Numerical results and discussions

The present study was performed under similar to operating condition of an actual absorption chiller/heater was shown in Table 1. The model was solved using time step of 0.02ms. Fig. 3 shows the variation of solution outlet temperature during the time simulated. The outlet solution temperature reaches to stable value and has a stable periodic behavior after some droplets felt out at solution outlet.

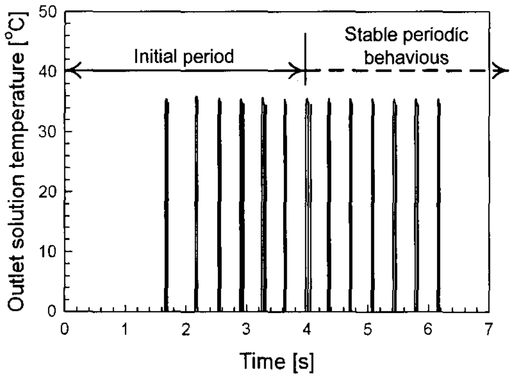

Fig. 3 Temporal variation of outlet solution temperature

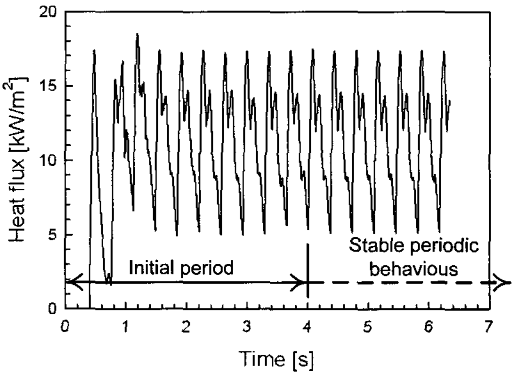

Fig. 4 Temporal evolution of heat flux

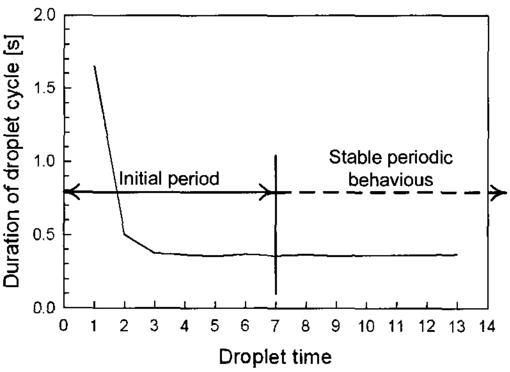

Fig. 5 Duration of two successive droplets

Table 2 Summary of solution droplet during time simulated

Droplet time	Time to fall out [s]	Duration of droplet cycle [s]	Average outlet solution temperature of one droplet cycle [°C]	Average heat flux of one droplet cycle [kW/m^2]
1	1.6520	1.6529	35.2645	8.21960
2	2.1540	0.5020	35.6224	11.2053
3	2.5284	0.3738	35.3245	11.3148
4	2.8921	0.3636	35.1951	11.3663
5	3.2472	0.3552	35.1597	11.5212
6	3.6150	0.3677	35.1317	11.3152
7	3.9726	0.3576	35.0929	11.6319
8	4.3380	0.3657	35.2797	11.4062
9	4.6940	0.3557	35.1632	11.4850
10	5.0555	0.3615	35.2731	11.4409
11	5.4152	0.3597	34.9483	11.4646
12	5.7759	0.3607	35.0554	11.4410
13	6.1439	0.3679	35.1960	11.3171

The evolution of the heat transfer from solution film to tube wall during the time simulated is shown in Fig. 4. The evolution of the heat flux has the same behavior with the variation of the outlet solution temperature that is after some initial droplets, the heat flux becomes stable periodic variation with time.

Fig. 5 shows the duration of two successive droplets. The droplet of solution at solution outlet becomes regularly after an initial period. Therefore it is clear that, the solution droplets and falling films have a periodic behavior with time. It means this is a periodic unsteady flow.

Table 2 shows the typical data of solution film during time simulated. The periodic behavior of solution droplets and falling films begins at around droplet seventh. A typical droplet formation cycle required around 0.362s when the flow reaches the stable periodic behavior whereas it took about 1.653s for the first droplet when solution begins coming from the tray hole.

3.1 Description of solution droplets and falling films

Fig. 6 shows the visualization of solution droplet and falling film for the first droplet. The solution came from the tray hole and the droplet is formed and felt to the first tube surface (frame a-f). The solution spread as a film on the first tube surface and move down to the bottom of the first tube (frame g-i). After receiving one more droplet from the tray hole, the solution on the first tube surface is then felt to the second tube surface (frame j-r). This process is continued in the third tube and finally the solution felt out (frame s-aj).

Fig. 7 shows the visualization of solution droplet and falling film for one typical droplet cycle which is chosen at cycle eleventh. Since solution has already remained on the tube surfaces therefore the droplet time of one droplet cycle is much shorter than the first droplet.

In order to test the validation of the solution procedure, it is essential that CFD simulations must be compared with experimental data. Fig. 8 shows several selected frames of the simulation from the present study and high-speed video camera from the study of Killion et al.[3]. In this previous study, the flow visualization of aqueous Lithium Bromide solution falling over 15.9mm OD tubes using high-speed video was carried out. The frame (a) of Fig. 8 is collected from frame (h) of Fig. 7 shown the solution droplet formation at the bottom of the second tube. The frames

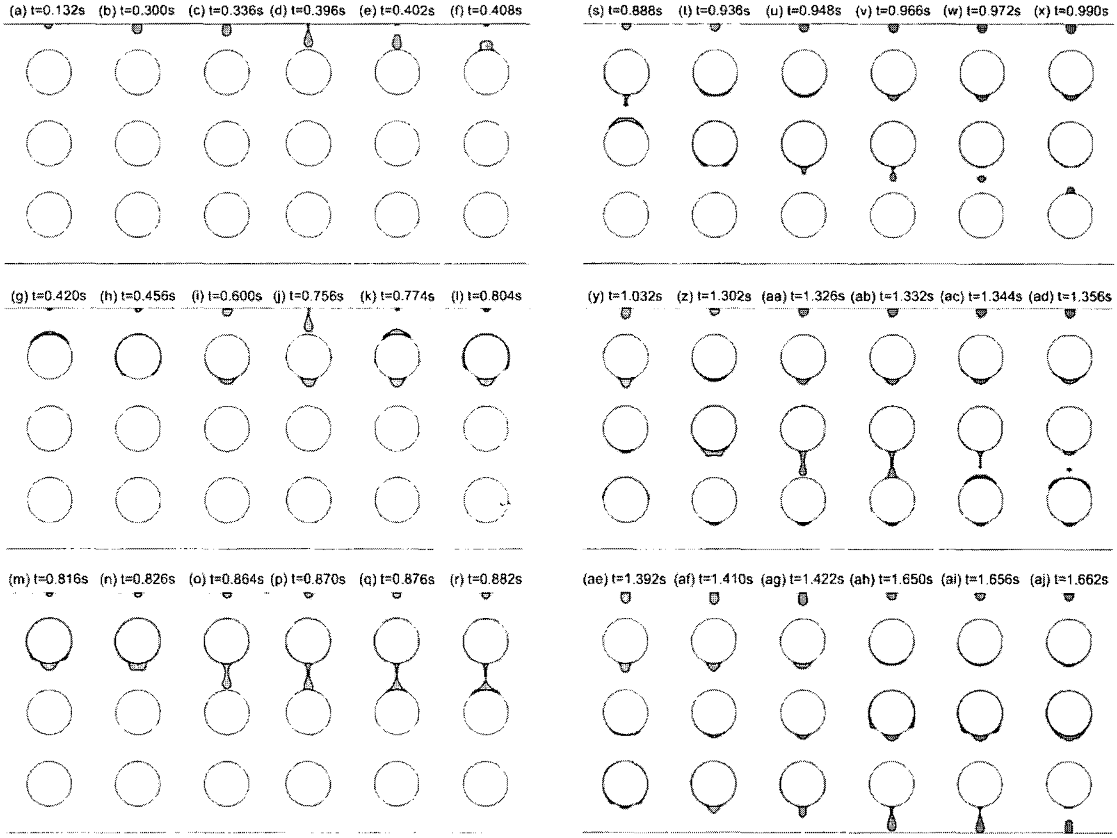

Fig. 6 Visualization of solution droplets and falling films for the first droplets

(b-c) of Fig. 8 are collected from frames (i-j) of Fig. 7 shown the fall of droplet at the bottom of the second tube to the top of the third tube. As shown in the figures, the shapes of solution droplet and falling film obtains from this simulation agrees well with those from visualization using high speed video camera.

The discussion of the solutions droplet and falling films on horizontal tube flow phenomenon has been described by Killion et al.[8] and are repeated here by using the results obtained from this study for clarify and also to evaluate the validity of the present model. The contribution of droplets forming at the bottom of the tube and the circumferential and axial waves and oscillations created on a smooth film due to droplet impact and detachment has been largely ignored by researchers modeling absorption. Models of falling film absorption on horizontal tubes invariably assume that the film is smooth and laminar.

3.1.1 Droplet formation, detachment and fall

By the effect of gravity force the droplet was formed at the bottom of the first tube as shown in frames (h-i) of Fig. 6. As more liquid enters the forming droplet, the distance from the tube to the tip of the droplet continues to increase and the tip of the droplet tends to a spherical cap as shown in frame (j-m) of Fig. 6.

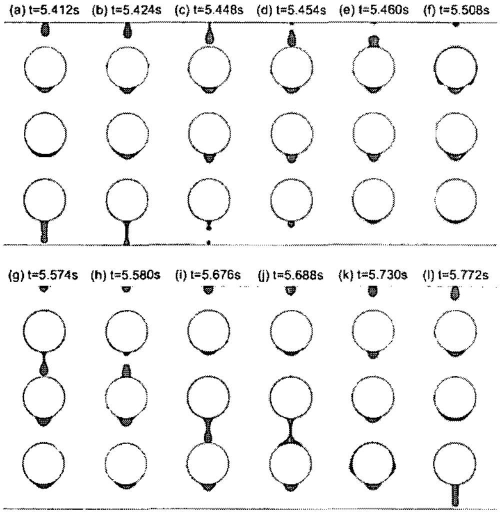

Fig. 7 Visualization of solution droplets and falling films for one droplet cycle

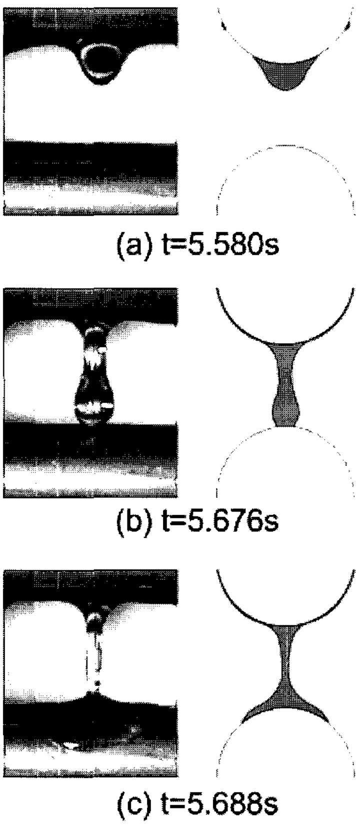

Fig. 8 Visual comparison of experiment with simulation

As the droplet continues to grow and extend away from the tube, the droplet will reach a critical volume, this appears around frame (n) of Fig. 6. When this occurs, the droplet starts to detach and its downward velocity begins to increases quickly. As gravity begins to accelerate the head of the droplet, the droplet pulls away from the tube faster than new liquid enters from the film. This causes necking in the liquid bridge between the droplet and the film on the tube as shown in frame (o) of Fig. 6. This thinning liquid bridge is extended by the motion of the droplet as shown in the frame (p-q) of Fig. 6.

As the bridge continues to thin, the competing surface tension forces eventually break the liquid bridge at a point close to the droplet shown in frame (r) of Fig. 6.

The velocity at the point where the liquid bridge breaks is extremely high and the recoil of the bridge is very fast shown in the frame (s) of Fig. 6.

The bridge then breaks into a number of satellite droplets of significantly less volume than the primary droplet shown in the frames (v-w) and (ac-ad) of Fig. 6 at the bottom of the second tube.

3.1.2 Impact and detachment related waves

Frame (j-k) of Fig. 7 show in great detail the behavior of the primary droplet and film during the impact phase. The assumption usually employed in models is that the solution flows as a smooth film and without axial variations around the tube. These figures clearly show the limitations of this assumption. When the droplet impacts the film, it immediately begins to deform around the tube shown the frame (j) of Fig. 7 at the top of the third tube and begins to form a saddle shaped wave shown in the frame (k) of Fig. 7 at the third tube side.

The detachment of a pendant drop causes a disturbance at the bottom of the tube, which generates waves on the film above and to the side. This process is shown in frame (k-l) of Fig. 7 at the bottom of the second tube.

3.2 Heat transfer

Fig. 9 shows the average value of the outlet solution temperature including the average outlet solution temperature of one droplet cycle and the average outlet solution temperature of overall periodic unsteady process. As shown in the figure, the outlet solution temperature is 35.135°C whereas the inlet solution temperature is 47°C and the wall temperature is 32°C.

The average value of heat flux is shows in Fig. 10. The heat transfer happen strongly or weakly depends on the heat transfer area on the tube surfaces where the solution films cover, the maximum heat flux is 17.386 kW/m^2 whereas the minimum heat flux is 5.093kW/m^2. The average heat flux of the overall periodic unsteady process is 11.426 kW/m^2.

The heat transfer coefficient is determined by the following equation

$$h=\frac{\bar{q}}{\frac{\Delta T_{in}-\Delta T_{out}}{\ln\left(\frac{\Delta T_{in}}{\Delta T_{out}}\right)}} \quad (4)$$

where $\bar{q}$ is the average heat flux. $\Delta T_{in}=T_{in}-T_{wall}$ and $\Delta T_{out}=T_{out}-T_{wall}$ are the difference between the solution and the wall temperature at the inlet and outlet, respectively. From this equation, the heat transfer coefficient is calculated and has the value of 1.7kW/m^2K.

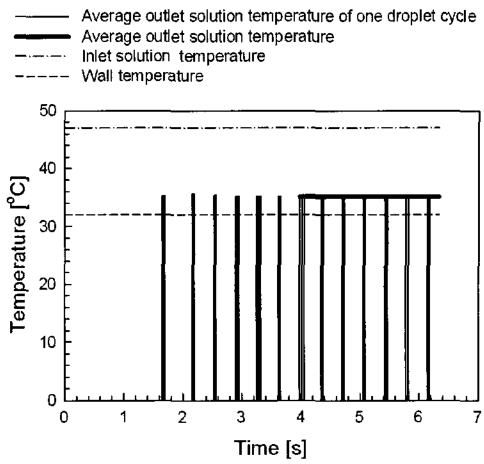

Fig. 9 Variation of average outlet solution temperature

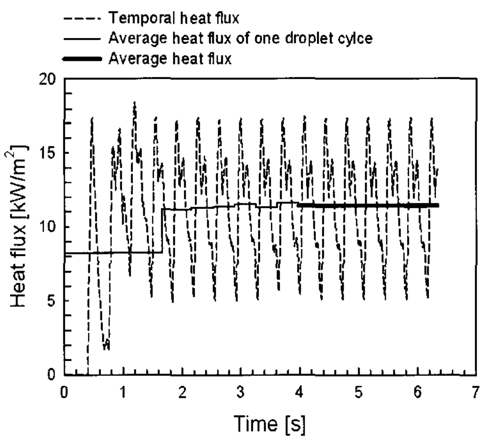

Fig. 10 Variation of average heat flux

4. Conclusions

A model of solution falling films and droplets in horizontal tube banks of absorber has been developed. The results can be summarized as follows:

Flow visualization studies shown that the solution droplets and falling films have revealed some of the complex characteristics. These include the development of a droplet formation, the progression of shape transitions through the development of the droplets, the stretching of the liquid bridge between the tube and droplet, the breakup of the liquid bridge and generation of satellite drops, the waves generated upon droplet impact including the characteristic saddle wave, the waves and oscillations generated from droplet detachment and bridge breakup. Therefore it is necessary to consider the details of the droplet and falling film behavior which has largely been ignored in previous studies to advance the state of the art in modeling absorption in these systems.

The outlet solution temperature and heat flux from solution film to the tube wall have a stable periodic behavior with time. And the droplet of solution becomes regularly after an initial period. A typical droplet formation cycle required around 0.362s. Therefore it is clear that, with the numerical conditions similar to the operating condition of an actual absorption chiller/heater, the solution droplets and falling films is a periodic unsteady flow.

Acknowledgements

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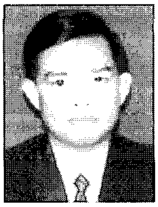

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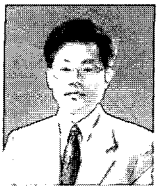

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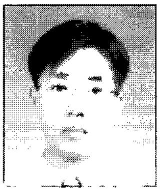

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