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THE MODELING OF THIN FILM HEAT EXCHANGERS

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Abstract

The steady and dynamic behavior of thin film evaporators and condensers are simulated with a general thin film heat exchanger model. The dynamics of the gravity-controlled falling laminar film on horizontal or vertical tubes are studied in detail. For a first approach or for a slow transient a single-lumped model can be used. For a refined simulation or for a severe transient a grouped model is proposed. The grouped model preserves the unique feature of delay-time and wave-distortion of a transient, which was observed in a separate precised analysis.

The thin film heat exchanger models are used in the dynamic simulation computer programs ODSP3 and OSCAR which were established at CMU for OTEC systems. Typical results are presented to demonstrate the capability of the model.

Introduction

The design of shell and tube condensers has achieved substantial attention in the past as indicated in the review paper [1]. The thin film evaporators also have been studied extensively in the area of desalination and OTEC applications [2,3]. However, appropriate literature are not available for dynamic modeling of these components.

The evaporator in an OTEC system generates vapor from a flowing liquid film on horizontal or vertical tubes. The vapor, passes the turbine and at a later point, condenses in the condenser on the liquid films at horizontal or vertical tubes again. The common feature of evaporators and condensers is that the major transport process happens on the liquid films. Therefore, it becomes possible to simulate the dynamic behaviors of these components by a unified approach which models "Thin Film Heat Exchangers" in general.

In a thin film heat exchanger the motion of a liquid film can be influenced by the motion of the flowing vapor. However, near the central region of the bundle where vapor flow is insignificant the film falls mainly due to gravity. The schematic of the flow regimes in a thin film evaporator is illustrated in Figure 1.

At close to the edge of the bundle the vapor cross flow can be strong enough to break the liquid film by shear stresses. The transition of film flow between the shear-controlled and gravity-controlled regimes on horizontal tube bundles can be well described by a dimensionless gas velocity Jg*[4]. In addition, the liquid entrainment and the breakdown of films have been analyzed in [5,6], respectively. In spite of this, the general behavior of this shear dominant film flow is still not well known.

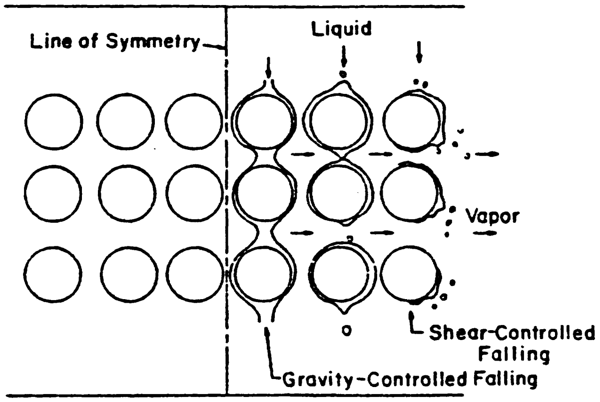

Figure 1. Flow Regimes in a Thin Film Heat Exchanger.

On the other hand, the gravity-controlled steady state film flow and heat transfer behavior has been studied extensively in the past [7,8] and the dynamic simulation based upon this flow regime could be more feasible at the present time. In the present unified approach, a column of horizontal tubes or a single piece of vertical tube in an evaporator or a condenser is considered. Liquid film falls vertically due to gravity. The film thickness either increases or decreases depending upon whether the unit is a condenser or an evaporator.

Practically, in the thin film OTEC evaporator the feeding rate of the working fluid onto the bundle is considered as one of the most effective parameters for the control of the system. Generally, slow transients of the liquid film flow occur at the conventional operations of an evaporator; however, severe film transients occur at emergency operations. For example, a sudden drop of the load to the generator causes the turbine to overspeed. The opening of the bypass valve and the shutoff of the feeding on evaporator react in the order of 1 second. The liquid film on tubes experiences severe transients.

The classification of the flow transients in a thin film heat exchanger can be performed according to the following argument. At steady operation the liquid is fed to the top of the bundle with sufficient over-flow. The time required for the liquid traveling to the bottom of the bundle is, typically, in the order of 5 seconds. For a variation of feeding with a characteristic time longer than 5 seconds, the quasi-steady approach for the film dynamics can be used with reasonable accuracy. For the variation of feeding with a characteristic time less than 5 seconds, the quasi-steady approach does not give a reasonable result. More precised modeling will be necessary.

In the quasi-steady approach the flow transient is slow. At any moment the flow conditions on all the bundle are very similar. Therefore, all the tubes in a bundle can be considered as a single representative tube. In other words, the whole bundle in a thin film heat exchanger can be simulated by a single-lumped tube with steady state solution applied at each moment.

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At severe transients the model should consider the whole horizontal tube column as a series of grouped-control-volumes with each group containing several tubes. The most accurate analysis considers each horizontal tube as a group. If only one group 1s used for whole column this model becomes a single-lumped approximation. The practical selection of the number of groups is based upon the typical transient of the feeding which we are interested in. With these lumped subsystems arranged in a vertical series the time response of a film is simulated while keeping calculational effort to a minimum.

In each lumped subsystem the film thickness and the heat transfer coefficients are taken from the results of theoretical studies or empirical correlations. The dynamic behavior of the film is studied with quasi-steady analysis, and some typical results of the model will be compared with detailed exact calculations of transients.

In the following sections the quasi-steady approach and the grouped approach of the film transients will be presented in detail. Additionally, the results of a separate detailed analysis on film transients are indicated as an reference to the proposed model. The integration of these models to the heat exchanger model is illustrated in the section of "The Modeling of Heat Exchangers." The heat exchanger model then will be used in some dynamic simulation computer programs established at CMU. Finally, a typical result of the dynamic behavior of the thin film exchanger in an OTEC system is shown.

The Quasi-Steady Approach to Film Dynamics

A. Horizontal Tubes

Generally, the single-lumped approach and steady state results were used in the present case. The initial condition at x= 0 is that the inlet volume flow rate per unit length equals $2\Gamma_o$. At laminar flow with constant wall heat flux the film thickness δ is

$$\delta = \{[(\frac{3\nu\Gamma_o}{g}) - (\frac{q_w}{\rho_l h_{fg}})(\frac{3\nu R}{g})(\frac{x}{R})]/\sin(\frac{x}{R})\}^{1/3} \tag{1}$$

where v is the kinematic viscousity, q_w is the wall heat flux leaving the surface, p£ and hfg is the liquid density and latent heat of vaporization, R 1s the radius of the horizontal tube, and x is the distance measured from the too of the tube along the surface. We may set sin(£.) « 1 in the equation (1) for vertical tubes. In m£t cases, the rate of evaporation of the liquid on an horizontal tube is very much less than the liquid flow rate.

In some cases the tubes are coated with heat transfer augmentation material such that boiling occurs in the evaporator. The heat transfer coefficient of the boiling thin film can be put in a general form [9]

$$h = C(T_w - V)^n \tag{2}$$

In a condenser or when pure evaporation occurs in the laminar film the heat transfer coefficient is related to the film thickness as [10]

$$h = k/\delta \tag{3}$$

B. Vertical Tubes

Liquid falling on a vertical tube is very likely to be 1n wavy laminar flow or in turbulent flow. Correlations are presented here for smooth tubes. The film thickness is described as [11]

$$\delta/(\frac{\nu^2}{g})^{1/3} = 0.36(2\Gamma)^{0.55} \tag{4}$$

The heat transfer coefficient for wavy laminar flow 1s

$$h \approx 0.606\,(k^3 g^2/\nu^2)^{1/3}\,[\Gamma/\mu]^{-0.22} \tag{5}$$

and

$$h = 3.8\times10^{-3}(kW)^{3}\,(4\Gamma/\mu)^{0.4}\,(£)^{0.65} \tag{6}$$

for turbulent flow with laminar to turbulent transition [7] at

$$\frac{4\Gamma}{\mu} \approx 5800\,(\,)^{1.06} \tag{7}$$

Grouped Approach to Film Dynamics

In this approach lumped subsystems are assigned to several consecutive horizontal tubes or a section of vertical tubes. Figure 2 shows the schematic of the model. Within that subsystem, a proper delay time is chosen to take into account the free falling of liquid between horizontal tubes as well as the finite liquid flow velocity along the tube. When the number of horizontal tubes in a subsystem equals the total number of tubes in a column or the length of the vertical section equals the total length of the vertical tube, the present model corresponds to the single-lunped model. When there is only one horizontal tube in a suDsystem or when the length of vertical section in a subsystem, is very short the present model approaches the exact case.

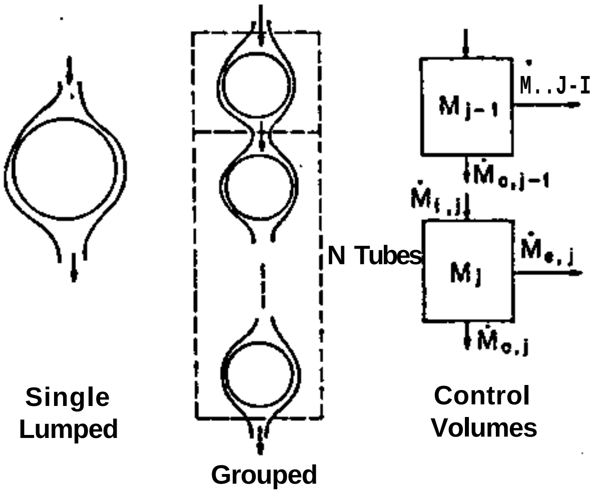

Figure 2. Single-Lumped and Grouped Models.

The mass balance of each lumped subsystem j can be written as

$$\frac{dM_j}{dt} = \dot{m}_{i,j} - \dot{V}_j - \dot{m}_{e,j} \tag{8}$$

where rrfi.j is the inflow to control volume j, ni_0.^ 1s the outflow from control volume j, $\dot{r}n$^j is positive for evaporation and negative for condensation. In order to solve this equation, all the $\dot{m}$'s must be present in terms of M's.

In the evaporator, dryout of the liquid film may occur during a transient. This corresponds to the case of Mj ^{s} 0 in that subsystem.

A. Horizontal Tubes

At Initial steady state, the total mass in the subsystem is

$$M_j = N_j \rho_\ell \int_0^{\pi R} 6(x)dx \qquad (9)$$

where N^ is the number of horizontal tubes in the control volume j. Using equation (1) for 6(x), with q* * o, we get

$$M_j = 2N_j\rho_\ell R\left[\frac{3\nu\dot{m}_{i,j}}{2\rho_\ell g}\right]^{-1/3} \int_{\Delta}^{ir-A} s1n\ y^{-1/1}\, dy \qquad (10)$$

The values of the A is assigned to be the half thickness of the falling film between horizontal tubes.

The flow rate at the inlet of subsystem j comes from subsystem j - 1 .

$$\dot{m}_{i,j}(t) = \dot{V}_{j-l}(t) \qquad (ID$$

In this subsystem, $\dot{m}_{o,j}$ is related to $\dot{m}_{i,j}$ by a delay time $\bar{t}$. That is

$$\dot{V}_j(t)\ s\ \dot{"}ij\{t"\wedge" \frac{1}{t^-} \int_{t-r} f\ \dot{V}_j(t)dt \qquad (12)$$

such that equation (8) becomes

$$\frac{dM_j}{dt} = \dot{m}_{o,j-1}(t) - \dot{m}_{i,j}(t-\bar{t}) - \dot{m}_{e,j}(t) + \frac{1}{\bar{t}_j} * \int_{t-T,_J}^{t} \dot{m}_{eJ}(t)\, dt \qquad (13)$$

There the evaluation of delay time $\bar{t}$ will depend upon the transient film behavior and the falling of the film between tubes.

For a quasi-steady system the delay time is the time for the fluid to travel through this subsystem.

$$\bar{t}_j = f(M_j) = \frac{N_j\ \pi R}{0.806}\left(\frac{3\nu}{g}\right)\left[\frac{2N_j\rho_\ell R}{M_j}\int_{\Delta}^{7T-A} \sin y^{-1/3}\, dy\right]^2 \qquad (14)$$

For a fast transient, the total mass Mj can vary as a function of time and the film thickness in the subsystem can vary as a function of location at a time. The selection of proper M- for the evaluation of t will not be straightforward. The exact solution of transient film motion was obtained by the authors [12]. Figure 3 shows the flow decay at various locations on a tube column. Also it appears that the thicker the film the faster it moves. For a film with non-uniform thickness the thicker film will catch up with the film in front of it. In other words, the thick part of the film travels with higher speed and dominates the major part of the transient behavior.

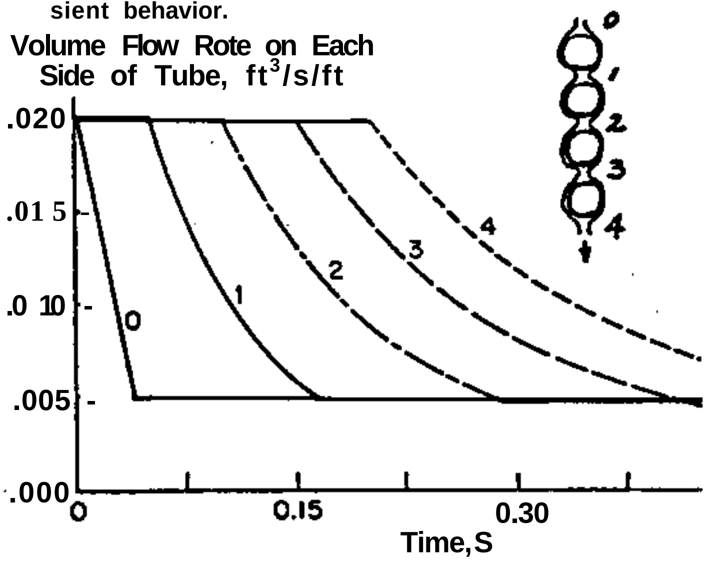

Figure 3. Evaporating Ammonia Film on One-Inch Tubes - Transient Analysis.

Since the flow has a delay time $\bar{t}$", the value of the total fluid mass for the equation £14) can be selected at the time t, or the time t-tj, or *zhe* time between these two limits. For example, a transient with increasing flow will have the total fluid mass at time t more than the total fluia mass at time t-tj. Then Mj(t) will be used for equation (14). A transient with decreasing flow will have the total fluid mass at time t less than the total fluid mass at time t-tj. Therefore, Mj(t-tj) will be used for equation (14;. In a general form we can ^*se* weighted combination for the time delay. That -jeans

$$\bar{t}_j = N_j\sqrt{\frac{2H}{g}} + \pounds f(M_j(t\sim V\} + (1"e)\ f(M_j(t)) \qquad (15)$$

where the first term at left sijde is due to the falling of film between tubes, $\bar{t}$ is solved by iteration in equation (15). The selection of c is cjite flexible. A smooth function is constructed for this purpose.

Finally, the evaporation rate can be calculated from

$$\dot{m}_{e,j} = \bar{h}\ 2N_j\pi R(T_w - T_y)/h_{fg} \qquad (17)$$

where

$$h = \frac{1}{\pi R}\int_0^{\pi R} h(x)dx \qquad (18)$$

with h(x) given from equations (2) *or* (3) and presented in terms of Mj.

A typical result of the variation of flew rates on a subsystem containing 20 consecutive hcrirental tubes is shown in Figure 4. The effect of *ca'.zy* time is clearly presented.

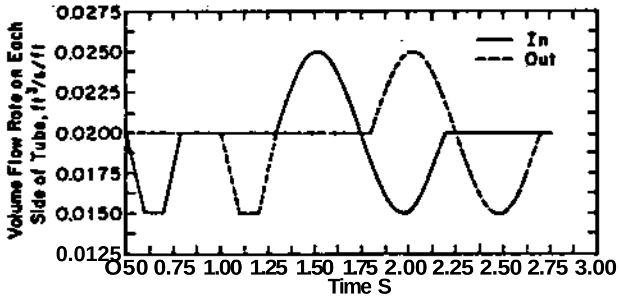

Figure 4. Evaporating Ammonia Film on 20 Consecutive One Inch Tubes-Result of Grouped Model.

B. Vertical Tubes

The same equation (8) can be used for vertical tubes. The total mass in the subsystem is

$$- \; {}_{j}\pi D\delta\rho_{\ell} \tag{19}$$

Using equation (4) for 6, we get

$$M_j = 0.36\, L_j(\pi D\rho_{\ell})^{0.45}\left(\frac{\nu^{\ell}}{g}\right)^{1/3}\left(\frac{m_{o.j}}{\nu}\right)^{0.55} \tag{20}$$

The evaporation rate is then

$$\dot{m}_{evap.j} = \bar{h}\,\pi D L_j\,(T_w - T_v)/h_{fg} \tag{21}$$

and $\bar{h}$ is the averaged heat transfer coefficient using h(x) in equations (5) and (6).

The Modeling of Heat Exchangers

The models for the condensers and evaporators are complicated. Transient heat balances are formulated for the water, the tube, the ammonia liquid on the tube and the vapor in the vessel, and finally for the liquid in hotwell.

The transient heat balance of the water considers the heat transfer to the tube and the incoming and outgoing enthalpies of water. To approximate the dynamic behavior, the transit times for the water are introduced as a time delay. The transient enthalpy balance for the aumonia liquid on tube and the ammonia vapor in the vessel considers the heat transfer from tube to vapor, liquid feed onto the tube and draining to the hotwell, evaporation from the hotwell, and the vapor leaving the vessel.

Mass balances are also formulated separately to describe the holdup for the vapor, the liquid ammonia on the tube, and the liquid in hotwell. Additionally, the state equation for the vapor temperature 1s written with the assumption that the vapor in the condenser is in the saturated state and also that it follows the ideal gas law.

In general, this model can be applied to both the condenser and the evaporator. Specific consideration that the condenser does not have liquid feed onto the tube and no vaDor leaves the vessel. On the other hand, no vapor comes into the evaporator. Under normal operating conditions the evaporator will have ammonia transport from the liquid film to vapor in vessel; this transport will be a negative quantity for the condenser.

The liquid in the hotwell will flash when the vessel pressure is reduced to a value lower than the saturation pressure of the hotwell liquid. Also at some conditions, the evaporator may operate at a low recirculation rate and the tube may experience partial or complete dry-out during transients. Since the exact relationship between the heat transfer and film flow during partial dryout is not available in the open literature, only complete dry-out is modeled.

The details of the heat exchanger modeling 1s presented in the Reference [13].

Results

Two computer programs were established at the Carnegie-Mellon University for the dynamic simulation of the OTEC power plants. The program ODSP3 [14] used the single-lumped approach for modeling the heat exchanger transients. The program OSCAR [13] uses the grouped model in simulation.

A typical OTEC closed cycle loop contains an evaporator and a condenser with the turbine in between. There is also a by-pass valve installed between the evaporator and condenser. At a hypothetical accident the load of generator will be dropped and the turbine rotation may speed up drastically. At this moment, the by-pass valve will be opened and the feeding of ammonia to the evaporator will be stopped. The vapor pressure in the evaporator will tend to decrease. The vapor pressure in the condenser will increase at a early time due to the opening of the by-pass valve. But, eventually, the pressure in condenser should decay because the pressure in evaporator also decays.

Figure 5 shows the results of this calculation. The action of by-pass valve and the valve to evaporator was initiated at time 0.5S after the drop of the load. The dynamic response of the evaporator and the condenser perform well as we expected.

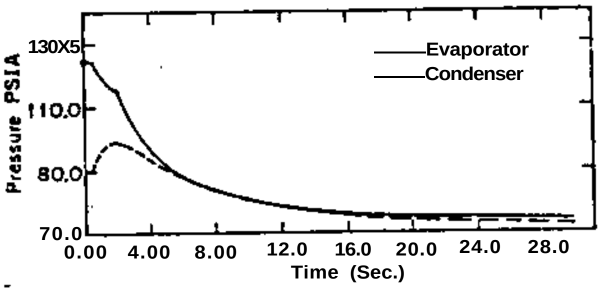

Figure 5. The Pressures in Evaporator and Condenser at a System Transient.

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References

1. Butterworth, D. ."Development 1n the Design of Shell and Tube Condensers,[11] ASME Paper No. 77-WA/HT-24.
2. Fletcher, L.S., Sevnas, V., and Parker, W., "Evaporation Heat Transfer Coefficients for Thin Sea Water Films on Horizontal Tubes," Ind. Eng. Chem. , Process Des. Dev., Vol.14, NO.4 (1975), pp.411-416.
3. Ganic, E.N. and Czikk, A.M., "An Analytical Model of the Sprayed Bundle Evaporators," Union Carbide Linde Division.OTEC Contract E(49-18)-2448.

4. Ishihara, K., Paten, J., and Taborek, J., "Critical Review of Correlations for Predicting Two-Phase Flow Pressure Drop Across Tube Banks," ASME Paper No.77-WA/HT-23.

5. Yung, D., Lorenz, J., and Gamic, E., "Vapor-Liquid Interaction and Entrainment in Shell-and-Tube Evaporators," ANL-OTEC-78-2.

6. Ihiratowicz, E., Gumkowski, S., and Mikidlewicz, "Experimental Study of Evaporation and Breakdown of Thin Liquid Films Driven by Shear Stresses," ASME Paper No.77-WA/HT-7.

7. Chun, K. and Seban, R., "Performance Prediction of Falling Film Evaporators," Trans. ASME J. of Heat Transfer, Nov.1972, pp.432-436.

8. Lorenz, J. and Yung, D., "An Analysis of Heat Transfer in Horizontal Tube Falling Film Evaporators," ML-OTEC-78-1.

9. Collier, J., "Convective Boiling and Condensation,[11] McGraw Hill Company, 1972.

10. Nusselt, W., "Die Oberflachenkondensation des Wasserdampfes," Zeitschr. Ver.deutsh. Ing. ,60, 541 and 569 (1916).

11. Seban, R., "Transport to Falling Film," Paper K-30, 6th Int. Heat Transfer Conference (1978).

12. Yao, S.C. , Chao, N.H. and Westerberg, A.W., "Transient Behavior of Condensing or Evaporating Films on Horizontal Tubes," 2nd Multi-Phase Flow and Heat Transfer Symposium, Miami Beach, April 1979.

13. Westerberg, A., Suuberg, E. and Yao, S., etal, [H]A Dynamic Simulation Program for OTEC," CMU-Rept. OTEC Contract No. EG-7-03-C1569.

14. Westerberg, A.W., Yao, S.C, et al., "Six Month Report for OTEC Dynamic and Control System Modeling," CMU-Rept. OTEC Contract No. DOE EY-76-S-02-2641-A004, September 1978.