TRANSIENT BEHAVIOR OF CONDENSING OR EVAPORATING FILMS ON HORIZONTAL TUBES

by

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May 1979

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Present at 2nd Multiphase Flow and Heat Transfer Symposium,
Miami Beach, April 1979.

ABSTRACT

An unified analysis is performed for transient liquid film behavior under gravity-controlled laminar flow on horizontal and vertical tubes. The film thickness may either grow or diminish for condensing or evaporating conditions respectively. The instantaneous local film thickness is described by the transient continuity equation where the velocity profile is assumed to be quasi-steady. This governing equation is a first order quasi-linear partial differential equation of the hyperbolic type.

Solutions obtained by the Method of Characteristics show that a wave on the film distorts gradually and will eventually behave like a shock discontinuity at its front, followed by a smooth expansion wave. This analysis also illustrates the distinct time delay of flow transients,

INTRODUCTION

The understanding of falling liquid film behavior for various flow transients is of great importance to the dynamic modelings of thin film evaporators, conventional condensers, desalination systems, or ocean thermal-energy power generation systems. For example, in thin film evaporates the feeding rate of the working fluid onto the tube bundle is considered as one of the irost effective means for control of the system. Generally, slow transients of the liquid film flow occur during conventional operations; however, severe film transients happen during emergency operation.

The steady-state design of shell and tube condensers has acheived substantial attention in the past as indicated in the reveiw paper [1]. The steady state performance of thin film evaporators also has been studied extensively in the area of desalination [2] and ocean thermal-energy power generation systems [3]. However, appropriate literature is not available for the dynamic behavior of these components.

In a thin film heat exchanger the motion of a liquid film can be influenced by the flowing vapor. However, near the central region of the tube bundle where vapor flow is insignificant the film falls mainly due to gravity. Near the edge of the bundle the vapor cross flow can be strong enough to distort the liquid film flow by the shear stress. The transition of film flow between the shear-controlled and gravity-controlled regimes on horizontal tube bundles is well described by a dimensionless gas velocity as proposed in [4]. The cross vapor flow may also cause the film break-down as described in [5]. In

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addition, at high vapor flow the liquid film on the tube or between the horizontal tubes may be displaced or disintegrated, and the liquid may become entrained by the flowing vapor [6]. In general, the behavior of shear-dominated film flow is not well understood. However, the steady-state behavior of gravity-controlled film flow and heat transfer has been studied extensively in the past [7, 8].

The well known steady-state solutions of the film behavior can be used to approximate the quasi-steady phenomena of a falling film at slow transients. For this condition, the dynamic model of a horizontal tube bundle in a thin film heat exchanger can be represented by a single tube using a lumped approach. This kind of approach has already shown distinct success in a dynamic modeling computer program ODSP which was established by this research group at CMU [9].

It is important to distinguish slow and fast transients in a flowing film. The film flows with a characteristic traveling time which is typically the time required for the liquid to travel from the top to the bottom of the bundle. On the other hand, the flow rate of the film may also have a characteristic transient time due to a change of the feeding rate in an evaporator or the condensing rate in a condensers. When the characteristic transient time is much longer than the characteristic traveling time, the quasi-steady analysis for film dynamics is a reasonable approach. If the characteristic transient time is much less than the characteristic traveling time of a thin film, the transient is considered to be fast and the quasi-steady approach will not be adequate. More precise modeling is then necessary.

The transient analysis of thin film has received relatively little attention in the past. Particular situations have been studied. For example, the motion of liquid film draining from a vertical wall has been calculated using similarity analysis [10]. However, practical applications require knowledge of the film behavior for various transients. There is neither experimental inforamtion nor appropriate analytical results available for the general transient phenomena of falling film in the open literature, For this reason, an analytical study is now performed for the general transient behavior of thin films.

FORMULATION

When condensation or evaporation occurs on a thin liquid film the film thickness grows or diminishes along the stream respectively. The rate of condensation or evaporation depends upon the heat transfer resistance across the thin liquid film. For both the cases of condensation and evaporation (non-boiling), the heat transfer of a laminar film is limited by the heat conduction across the film. Due to this fundamental similarity between condensation and evaporation it should be possible to study the dynamic behavior of a condensing or evaporating film with a common approach.

The present analysis is applied to a liquid film in laminar flow. In a horizontal tube bundle the film undergoes free fall between tubes. The flow distance on the surface of each tube is always short so that the film is usually in laminar flow even at high flow rate. In a vertical tube bundle the film flow is laminar if the flow rate is low. Therefore, the present analysis is good for horizontal tubes in general and good for vertical tubes at low flow rates.

There exist some complicated flow phenomena for a flowing film. It is noticed that frequently the liquid detaches from the bottom of a horizontal tube in the form of drops instead of as a uniform liquid film. Also the space between the locations where drops detach is governed by the Taylor instability consideration. Therefore, the liquid distribution to lower tubes is likely to be non-uniform. Furthermore, at the higher flow rate in a laminar regime, disturbances to the film may grow and develop into waves. This is a wavy laminar flow. Occasionally, when the tube wall temperature is high, moderate boiling may occur on the surface in the thin liquid film. The liquid flows between the bubbles, which is similar to the flow on a very rough surface. As a result, the effective drag of the tube will be greatly increased. In a large thin film heat exchanger the vapor flows with a substantial speed in the bundle. The motion of liquid film could be influenced by the shear of the vapor such that film breakdown or liquid entrainment might occur.

In the present analysis it is assumed that all the above complications do not exist. In other words, the liquid falls between tubes as a smooth film; the flew is not in the wavy laminar regime; nucleate boiling does not occur, and shear on the film by the flowing vapor is negligible.

With the above assumptions we analyze the transient laminar flow of thin film on a horizontal tube. The formulation for the film flow on a vertical tube is a special case of the corresponding horizontal tube analysis. A boundary layer approach is used, and the coordinate system is illustrated in Figure l(a). The transient momentum equation of thin film flow on a horizontal tube is written as

i t + u i 7 + v W = 9 Sin R + v ^2 CD

The same equation can be used for film motion on a vertical tube by simply setting sin 21/R to 1.

With a quasi-steady approximation to the momentum equation the time derivative term is neglected. Considering the small thickness of the film the viscous drag term and gravitational force term are most important. As a result, we simplify the momentum equation to

9 S1n ft + V $ " o (2)

with the boundary conditions of non-slip at wall and no vapor shear

$$u = 0 \quad \text{at} \quad y = 0 \qquad (3)$$

fjj- = 0 at y = 6 (4)

The solution for the velocity profile in the film is

u = - J sin (X/R) j- y²/2 · 6y-| (5)

A transient continuity equation is then used in present study. An integral analysis is applied to the film considering the effect of evaporation or condensation as an equivalent sink or source of mass. Figure l(b) shows a schematic for the mass balance.

$$-\frac{\partial\delta}{\partial t} = \frac{\partial}{\partial x}\int_0^{\delta} \;\cdot\;\cdot\;* \quad + \frac{q_w}{\rho_\ell h_{fg}} \qquad (6)$$

where 3w is the heat flux of the wall due to evaporation or condensation. % is positive for evaporation and negative for condensation. hf_g is the latent heat of evaporation.

The quasi-steady velocity profile in equation (5) can be used in the transient continuity equation (6) to form a transient equation for the film thickness 6 on a horizontal tube.

$$M \quad a \quad {}^{9\ \sin}\ ® \quad \delta^3\ ] + \frac{q_w}{\rho_\ell h_{fg}} = 0 \qquad (7)$$

where the 5 is a function of x and t. Once the film thickness 6(x,t) is obtained from this equation, the velocity profile can be evaluated from equation (5).

The corresponding equation for laminar film flow on a vertical tube is

$$\frac{\partial\delta}{\partial t} + \frac{\partial}{\partial x}\left[\frac{g}{-}\ \delta^3\right] + \frac{q_w}{h} = 0 \qquad (8)$$

the conditions for *6* at x = 0 and at t=0 are specified as initial conditions.

METHOD OF SOLUTION

Equation (7) is a first-order quasi-linear partial differential equation of the hyperbolic type. We attempted to solve this equation by conventional numerical methods. In all cases, severe numerical instability occurs.

Generally, the numerical calculation of a hyperbolic equation can be stabilized by introducing an equivalent "artificial viscosity" in the finite difference formulation [11]. Equation (7) was tried by the method of Lax [12] which approximates the time derivative as

$$\frac{\partial}{\partial t} \approx \frac{1}{\Delta t}\left[\delta_{i,j+1} - \frac{1}{2}\left(\delta_{i+1,j} + \delta_{i-1,j}\right)\right] \qquad (9)$$

$$= \frac{1}{\Delta t}\left(\delta_{i,j+1} - \delta_{i,j}\right) - \frac{1}{2\Delta t}\left(\delta_{i+1,j} - 2\delta_{ij} + \delta_{i-1,j}\right) \qquad (10)$$

$$\text{or} \quad \frac{\partial \delta}{\partial t} = \frac{1}{\Delta t}(\delta_{ij+1} - \delta_{ij}) - \left(\frac{\Delta x^2}{2\Delta t}\right)\left(\frac{\delta_{i+1j} - 2\delta_{ij} + \delta_{i-1,j}}{\Delta x^2}\right) \tag{11}$$

The last term contains the diffusion effect by this numerical scheme. Unfortunately, this method does not give stable solutions. This is possibly due to the highly non-linear term (δ^3) in the present problem.

The method of characteristics was ultimately used. Equation (7) is first written in the form

$$\frac{\partial \delta}{\partial t} + \delta^2 \frac{g}{\nu} \sin\left(\frac{x}{R}\right) \frac{\partial \delta}{\partial x} = -\delta^3 \frac{g}{3\nu R} \cos\left(\frac{x}{R}\right) - q_w/\rho_\ell h_{fg} \tag{12}$$

Then the equations for the characteristic lines become

$$\frac{\partial t}{\partial S} = 1 \tag{13}$$

$$\frac{\partial x}{\partial S} = \delta^2 \frac{g}{\nu} \sin\left(\frac{x}{R}\right) \tag{14}$$

$$\frac{\partial \delta}{\partial x} = -\delta^3 \frac{g}{3\nu R} \cos\left(\frac{x}{R}\right) - q_w/\rho_\ell h_{fg} \tag{15}$$

Letting the dummy variable S be t, we get

$$\frac{\partial x}{\partial t} = \delta^2 \frac{g}{\nu} \sin\left(\frac{x}{R}\right) \tag{16}$$

$$\frac{\partial \delta}{\partial t} = -\delta^3 \frac{g}{3\nu R} \cos\left(\frac{x}{R}\right) - q_w/\rho_\ell h_{fg} \tag{17}$$

Equations (16) and (17) are solved by iteration. Equation (16) is integrated for one time step using the Runge-Kutta method. A finite difference method is applied to equation (17) for the local δ value which will be used in equation (16) again for iteration. On convergence the characteristic line is obtained from equation (16) and the film thickness on the characteristic line is obtained from (17).

RESULTS AND DISCUSSION

Results are obtained by the Method of Characteristics. Equation (16) indicates that the thicker the film the faster it moves. For a transient with increasing flow the later thick film will tend to catch up the earlier thinner film. On a plot of the characteristic lines we find that they will eventually cross one another for conditions of increasing flow of liquid onto the tube. The calculation on or beyond the point of the intersection will be meaningless both mathematically and physically.

Practically, the transient behavior of a falling thin film is similar to the phenomena of wave propaaation in gas dynamics. The intersecting of characteristic lines corresponds to the formation of a shock wave in gas dynamics. Beyond that point the isentropic assumption of a wave is not valid. The shock equation has to be used to describe this irreversible process which shows a discontinuity of properties. Correspondingly, in falling film transients the intersection of characteristic lines implies the formation of an abrupt liquid front where the basic assumption of the boundary layer approximation used in this analysis is not valid.

Figure 2 illustrates the above behavior for a flowing liquid film where a "shock wave" occurs. The wave is distorted when it travels downstream. At the front, a liquid shock gradually forms; at the back, an expansion wave appears. Once the characteristic lines intersect, the shock front is established and the present analysis should not be performed further.

For conditions of flow decay the characteristic lines will not intersect one another. A situation similar to the expansion wave in gas dynamics occurs for the decayinq liquid film.

An example of flow decay transient on horizontal tube bundles is presented in Figure 3. An evaporating liquid ammonia film on one inch smooth tubes is considered. The feeding of liquid film at the top of the first tube is reduced at a fast rate. The film thicknesses near the bottom of each consecutive tube experiences a similar decay; however, a distinct time delay is observed for such a fast transient. The property of a time delay is not obtainable by the simply quasi-steady analysis. In addition, the rate of decay is also reduced for the film thickness. Figure 3 illustrates this phenomenon where the decay time of the film thickness is lengthened for lower tubes. A more detailed illustration is found in the Figure 4 where the flow decays to one quarter of its original value. The flow decay time is further lengthened in this case.

CONCLUSION

The transient behavior is analyzed for a gravity-controlled falling laminar film on horizontal or vertical tubes. The film may undergo evaporation or condensation. Solutions are obtained by the Method of Characteristics. The similarity of the film transient with respect to wave motion in gas dynamics is revealed. The time delay and the distortion of film thickness variations are also observed from this analysis.

ACKNOWLEDGEMENT

This material is based upon the work supported by the U.S. Energy Research and Development Administration/DOE under Contract No. EY-76-S-02-2641-A004.

NOMENCLATURE

g gravity
hfg latent heat of evaporation
<lw heat flux at the surface or over the film
R radius of the tube
5 dummy variable
t time
u film velocity, in x direction
v film velocity, in y direction
x location, alonq the stream of film flow
y location, normal to the surface
6 film thickness
v kinematic viscosity of the liquid
p^ density of the liquid

Subscripts

1 index for the increment in x
j index for the increment in time

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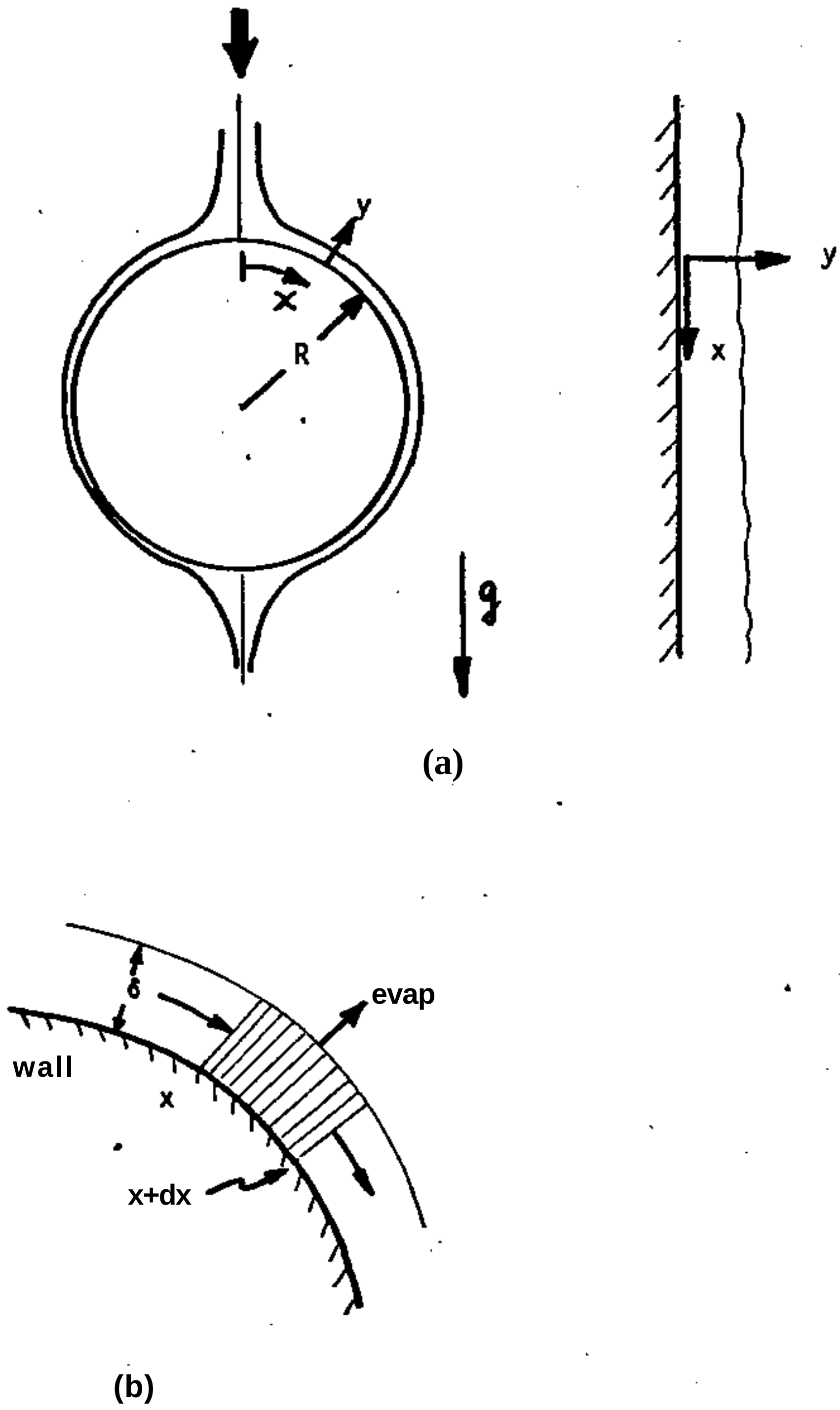


Figure 1. Thin Film Flow Model

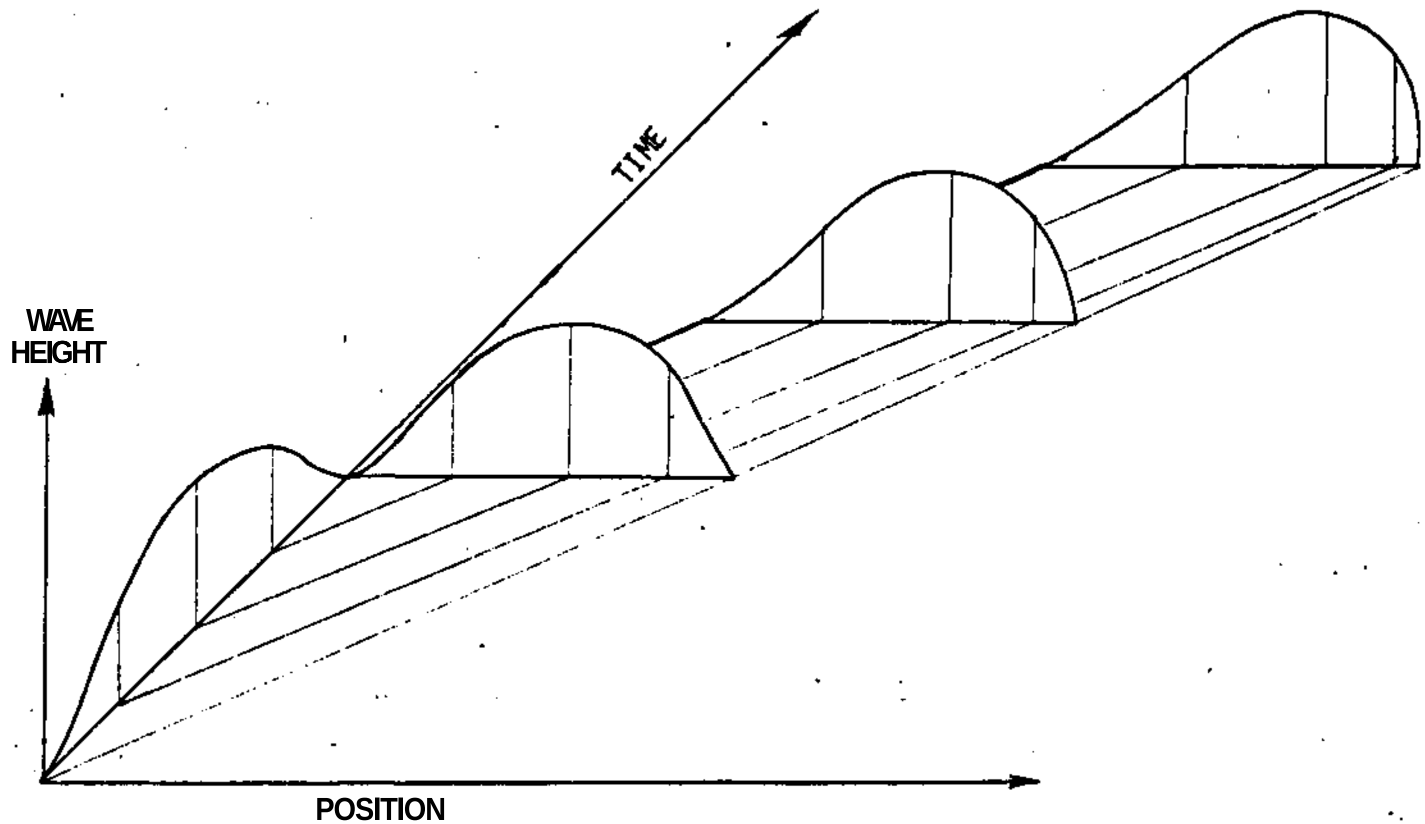
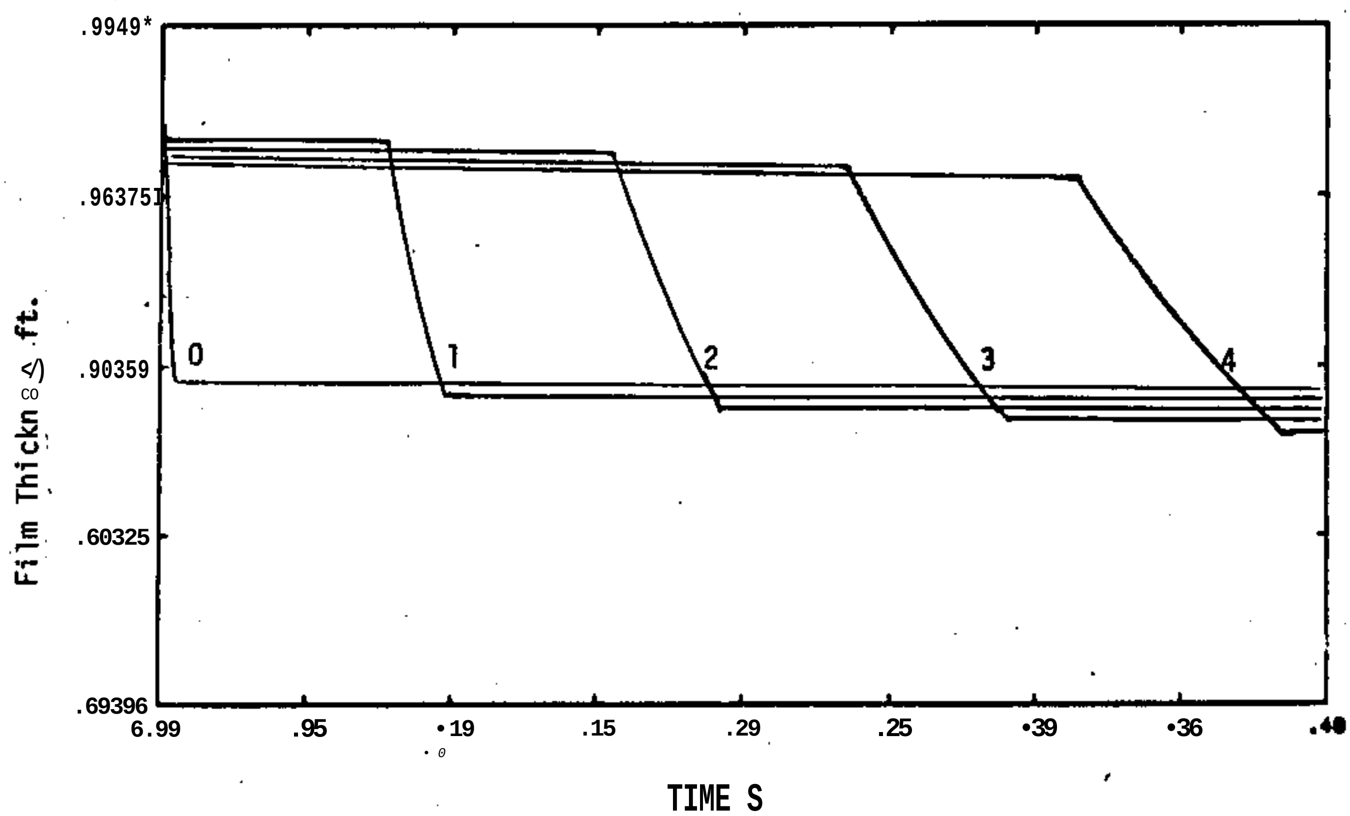


Figure 2. The Traveling of a Wave on the Falling Liquid Film



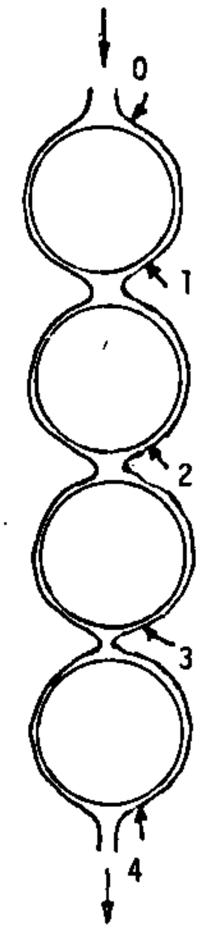


Figure 3. Evaporating Ammonia Film on One Inch Tubes.
(Small Reduction of Flow)

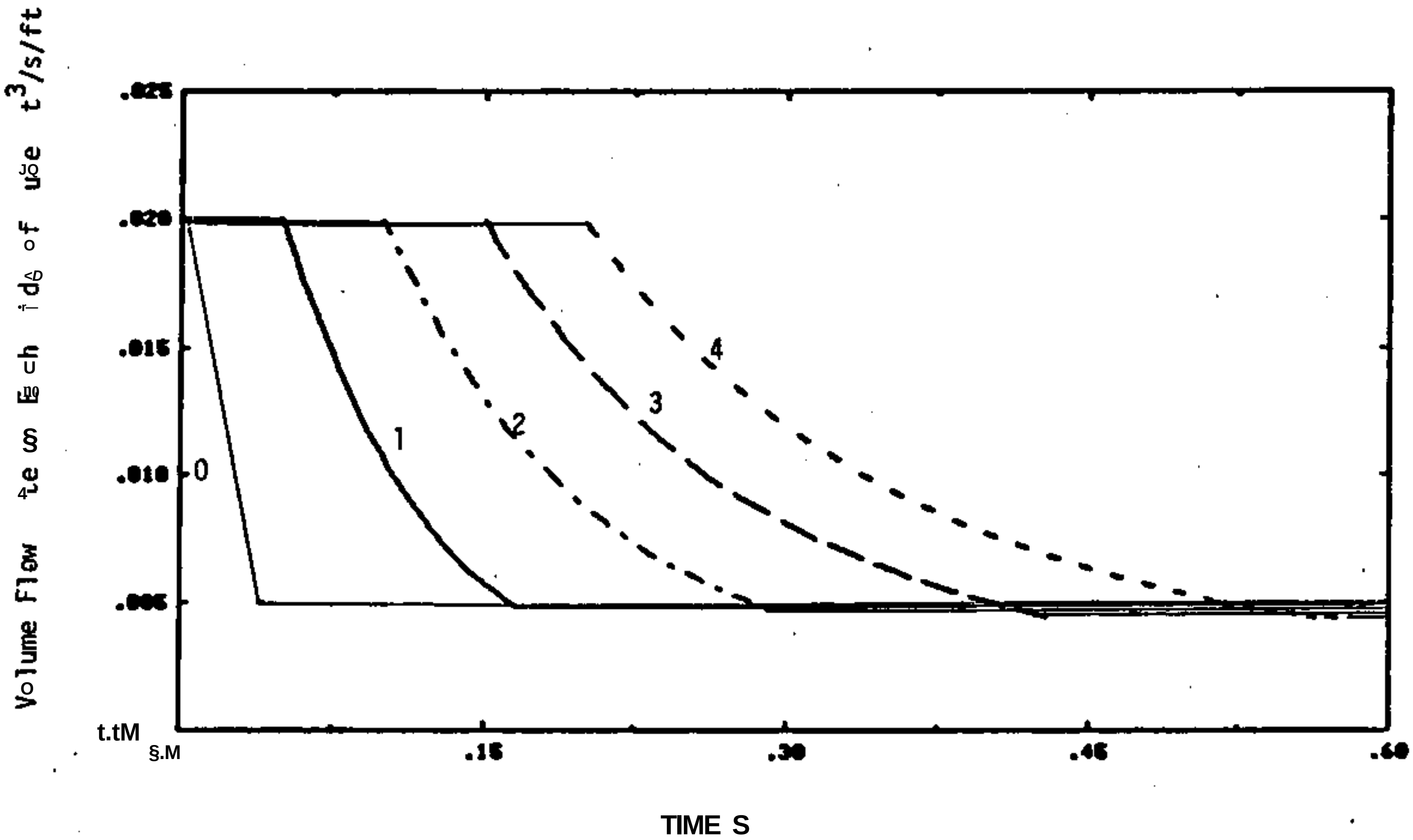


Figure 4. Evaporating Ammonia Film on One Inch Tubes
(Large Reduction of Flow)