AN EXPERIMENTAL STUDY OF FREE — SURFACE FILM FLOW OF WATER AND METHANOL ON THE OUTSIDE OF A VERTICAL CYLINDER

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Summary

The behaviour of water and methanol liquid films flowing down the outside of a vertical cylinder is investigated experimentally. Measurements of film thickness versus axial distance are made for water and methanol in the Reynold's Number range 300-1400. For a 100mm diameter cylinder and initial film thickness of 0.5 wave amplitudes of up to 0.7mm and wave frequencies of up to 67 cycles per second were mesured. Height of waves tend to increase with axial distance and bigger waves tend to have higher frequencies.

1. INTRODUCTION

The occurence and applications of liquid film flow has increased considerably as technology developed. Film flow is encountered in the process industries, cooling towers, evaporation condensers, chemical reactors, and the combustion chambers of rocket motors. In studying two-phase flow, it has been found that a detailed knowledge of the phenomena occuring in film flow, with or without an adjacent gas stream would assist greatly in understanding many of the more complex type of two-phase flow.

Many investigators have made theoretical studies of thin liquid film flow [1-4]. Empirical studies have also been conducted [2, 5]. Laminar and turbulent flow regimes have been identified and values of critical Reynolds Number quoted varies widely from 250-1500.

There are two main phenomena associated with film flow: [1] the variation of film thickness with distance along the flow and [2] the formation of surface waves.

The variation of film thickness is the easier pehnomenon and it has received more attention accordingly. The formation of surface waves is more complex. Some investigators [2,6,7,8] have suggested that the criterion for wave formation is that the Froude Number, Fr, is greater than unity.

However it remains very difficult to theoretically predict the nature of waves on thin films. Also empirical data in this regard are sparse.

In the present study an appropriate solution to the Navier-Stokes equation for film flow on a veritical cylinder is presented. Experimental measurements of film thickness versus axial distance were obtained for the flow of films of water and methanol on a vertical cylinder. Measurements of surface waves frequencies and heights are presented in the hope that such information may increase our understanding of film flow and may, for example, assist in the calculation of rates of heat and mass transfer through such wavy film interface.

2. PRESENT STUDY

2.1 An Approximate Solution of the Navier — Stokes Equations for Film Flow on a Vertical Cylinder

The flow is assumed to be incompressible, steady, axisymetric, laminar and the free surface is free of waves. Pressure gradients and surface tension forces are neglected.

We consider a cylindrical coordinate system in which r is radial, θ is azimuthal and x is the veritical axis of the vertical cylinder. (See Fig. 1). In the uniform flow region, the driving force is equal to the resisting friction force and by taking that the film thickness M is very much less than the cylinder radius R, it is possible to derive the Nusselt's result, and note that for a given flow rate the liquid film thickness is constant in the uniform flow region.

If we consider the accelerating region and apply the above mentioned assumptions the Navier-Stokes equations reduce to

$$\frac{u\partial v}{\partial x} = \frac{v\partial v}{\partial y} = -\frac{1}{\rho}\frac{\partial P}{\partial y} + \nu\left(\frac{\partial^2 v}{\partial y^2} + \frac{1}{y+R}\frac{\partial v}{\partial y} - \frac{v}{(y+R)^2} + \frac{\partial^2 v}{\partial x^2}\right) \tag{1a}$$

$$\frac{u\partial u}{\partial x} + \frac{v\partial u}{\partial y} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + g + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{1}{y+R}\frac{\partial u}{\partial y} + \frac{\partial^2 u}{\partial y^2}\right) \tag{1b}$$

and the continuity equation is

$$\frac{\partial v}{\partial y} + \frac{v}{y+R} + \frac{\partial u}{\partial x} = 0 \tag{2}$$

where u and v are the velocity components in the x and y directions, y is measured from the surface of the cylinder such that the radial distance r = R+y. It may be noted that the velocity component, u, along the cylinder axis is much greater than, v perpendicular to the axis.

i.e. $u >>> v$ (3)

By neglecting relatively small terms equation la disappears and, we arrive at the equations

$$\frac{u\partial u}{\partial x} + \frac{v\partial u}{\partial y} = g + \nu\frac{\partial^2 u}{\partial y^2} \tag{4}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

Equation (4) is integrated together with the boundary conditions

$u = v = 0$ at $y = 0$

$$\frac{\partial u}{\partial y} = \frac{\partial v}{\partial y} = 0 \text{ at } y = M \tag{5}$$

to obtain the equation

$$\left(\frac{\partial}{\partial x}\int_0^M u^2 dy\right) - \left(u_s\frac{\partial}{\partial x}\int_0^M u\,dy\right) - gM = \nu\frac{\partial u}{\partial y}\Bigg|_{y=0} \tag{6}$$

where u_s is the axial velocity at the free surface (y=M) at any section x.

Now, a velocity profile of the form

$$u = u_s(a\eta + b\eta^2 + c\eta^3) \tag{7}$$

is assumed

where $\eta = y/M$ and a, b, c are constants and are determined from the following three boundary conditions

$$\frac{\partial u}{\partial y} = 0 \quad \text{at } \eta = 1 \tag{8}$$

$$u = u_s \text{ at } \eta = 1$$

$$\int_0^M u\,dy = Q$$

where Q is the volume flow rate per unit wetted perimeter.

Using the assumed velocity relation equation (6) is reduced to an ordinary differential equation of the form

$$\frac{dM}{dx} = \frac{(C_4M^3 - C_5)}{(C_1M^6 - C_2M^3 - C_3)} \tag{9}$$

where $C_1 = \frac{5}{2625} g^2/\nu^2$; $C_2 = \frac{82}{2625} g(Q/\nu)$

$$C_3 = \frac{3264}{2625} Q^2; \; C_4 = \frac{4}{5g} \text{ and } C_5 = \frac{12\nu}{5} Q \tag{10}$$

Equation (9) is solved numerically with x as the independent variable.

2.2 Experimental Facilities and Procedure

The apparatus (See Fig. 2a,b) consists of a mild steel cylinder of 100 mm diameter and 950 mm long. The diameter is machined to tolerance limits of — 0.012 mm and — 0.034 mm and the surface is finished to 8 — 16 CLA. The cylinder is mounted on an adjustable base such that verticality is checked within 0.5 minute using a clinometer. An overhead tank consists of three main parts. The upper part is a barrel of 250 mm dia bore. The middle part has a cap that fits on to the top of the cylinder. This supports the tank in position and also provides for the centralization of the vertical cylinder passes through this orifice leaving an annular clearance of .5 mm with tolerance limits — 0.07 mm and + 0.034 mm. Provision is made for the approach flow to the slit to be free from eddies and turbulence, by putting honeycomb baffles in the overhead tank, using a 60 degree bevel and rounding off sharp edges in the slit approach section.

The circulating pump is mounted on a vibration absorbing bed and flexible plastic tubings are used for connections to and from the pump. The pump is driven by 0.2 kw constant speed motor which maintains a constant flow rate.

The probe consists of a 0.254 mm diameter platinum wire mounted firmly at the end of a micrometer arrangement; the whole of which is then clamped to the carriage of a cathetometer. This arrangement permits probe movement in three dimensions and facilitates measuring film thickness as a function of distance along cylinder axis. The platinum wire is insulated except at the very end of the tip, so that only the tip can detect contact with the liquid film.

An electronic sensing device was constructed to detect whether the probe is in contact with or out of the liquid film. A frequency signal is fed from a single Advance A.F. signal generator to the cylinder which is insulated from earth and held above ground potential. The signal is picked up by the probe when it is in contact with the flowing film. From the probe the picked-up signal is fed through a series of filter, Darlington pair, and Schmidt trigger. The output of the Schmidt Trigger was fed to a frequency counter and to an oscilloscope. The frequency is the "eye" of this sensing device.

The flow rate of liquid is regulated by adjusting the various controlling valves and measured by a rotameter. Contact of the micrometer probe with the cylinder wall is established by means of an avometer, the reading of the micrometer in this position being recorded as a 'reference zero'. The probe is brought away from the wall in predetermined steps and frequency counts per 100 second intervals recorded. In this way it is possible to determine the probe positions when waves are first detected and when the probe is just clear of the highest waves on the liquid film.

3. DISCUSSION OF RESULTS

3.1 M/R versus x/R relation

The dimensionless film thickness M/R is plotted against the dimensionless axial distance x/R. The Reynolds number Re defined as being equal to $\bar{u}\,\bar{M}/v$ is constant at all locations on the cylinder surface for each flow rate of a liquid. Both the wave amplitude and maximum frequncies for each particular Re are shown on the same figure representing the relation between M/R and x/R. Figures 3 to 5 are for water at Reynolds number 288, 613, and 932 respectively. The water temperature was 20°C, kinematic viscosity was .01002 Stokes and the surface tension was 72.75 dynes/cm; these physical properties being the same for the Reynold's numbers investigated. Figures 6 to 8 are for methanol and the Reynold's numbers investigated were 450, 893, and 1393. The kinematic viscosity of methanol was .00769 Stokes, the surface tension was 22.6 dynes/cm and the temperature was 15°C. On all of figures 3 to 8 the wave heights obtained experimentally are indicated by the horizontal lines together with the maximum frequencies at each position.

If mean film thickness is taken as the film thickness mid-way of the wave amplitude, it can be seen from figures 3 to 8 that the agreement between predicted and experimental film thickness is best at the higher Reynold's Numbers.

Figures 3 to 8, suggest that there is a core of the film free from waves along the whole length of the test section. Waves are superimposed on the core film. The wave amplitude tend to increase with axial distance. The maximum wave frequencies do not vary in any definite pattern, although there is a slight tendency for the bigger waves to have higher frequencies. It may be noted that the part of the film just after the slot opening has less waves and this wave-free part becomes longer as Re increases. It is suggested that the slot configuration and the initial velocity at this slot due to the velocity head in the overhead tank may be important.

The main contribution of this study is in providing data of wave amplitudes and frequencies which may be used for design purposes.

CONCLUSION

1. For the particular flow configuration studied, the part of the thin film immediately after the slot is free of waves. This wave-free part increases as Reynold's Number increases.
2. Waves are super-imposed on a core of film. The height of the waves tend to increase with axial distance from the slot.
3. There is a tendency for bigger waves to have higher frequencies.
4. The wave heights has a maximum value of 0.7 mm and a maximum frequency of 67 cps.

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NOTATION

f	Friction factor for film flow
Fr	Froude's number
g	Acceleration due to gravity
M	Film thickness
M_i	Initial film thickness (at x = O)
M_N	Nusselt film thickness
M_x	Film thickness at x
$\bar{M}$	Mean film thickness
M*	Dimensionless film thickness (M/R)
M***	Dimensionless film thickness (Mu_f/ν)
P	Pressure

Q	Volume flow rate per unit wetted perimeter
R	Radius of vertical cyliner and characteristic length
Re	Reynolds number
Re_{cr}	Critical Reynolds number of the onset of waves
Re_{crtub}	Critical Reynolds number for the onset of turbulence
r	Radial co-ordinate
t	Time
u	Velocity in the x-direction
U_f	Friction velocity
u_s	Surface velocity of film
$\bar{u}$	Mean film velocity in the x-direction
u^*	Dimensionless velocity (u/U)
U	Characteristic velocity
v	Velocity in the y-direction
v^*	Dimensionless velocity (v/U)
V	Volume flow rate
x	Coordinate in the direction of flow
x^*	Dimensionless distance in the x-direction (x/R)
y	Coordinate measured out from wall surface
y^*	Dimensionless distance from all (y/R)
θ	Inclination to horizontal or coordinate around cylinder
μ	Dynamic viscosity
ν	Kinematic viscosity
η	Dimensionless distance from wall (y/M)
ρ	Density of liquid

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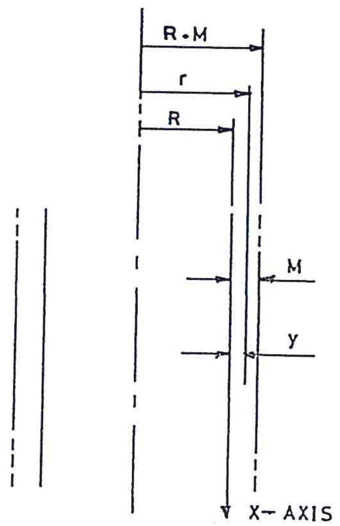
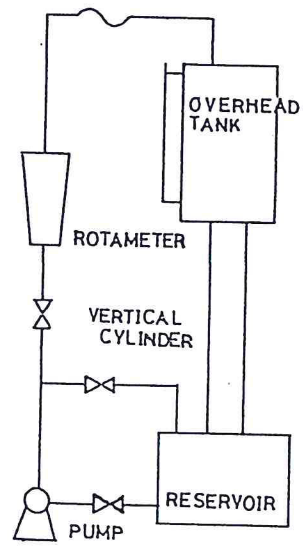


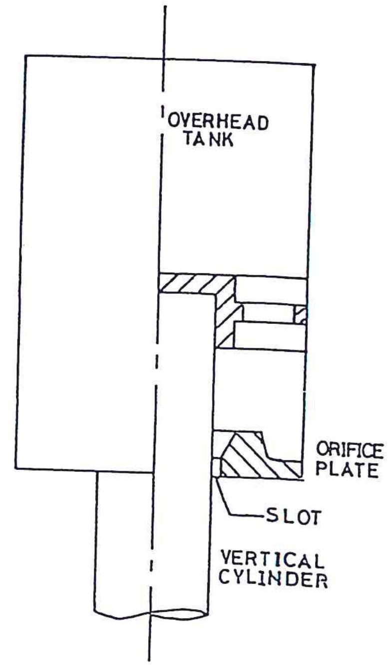
Coordinate system for film flow on a vertical cylinder

FIGURE 1



Schematic diagram of expe-mental set-up

FIGURE 2a



Sketch of overhead tank and vertical cylinder assembly

FIGURE 2b

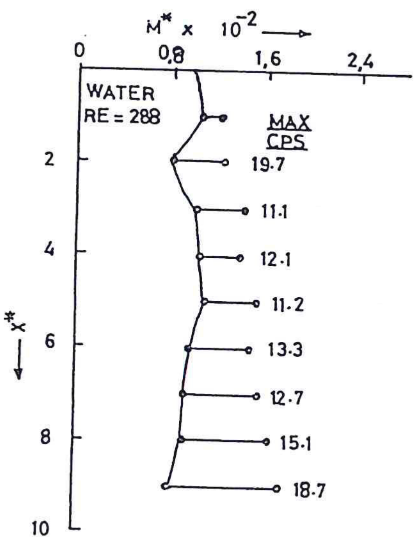
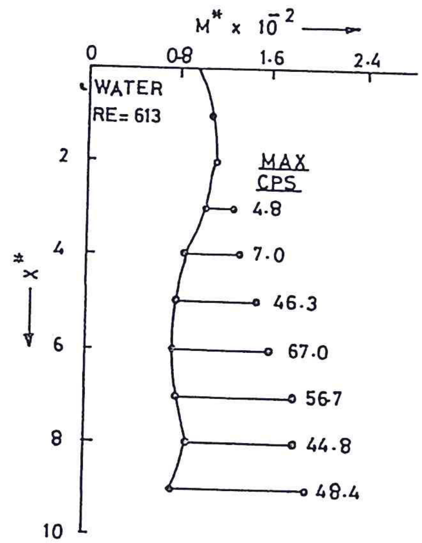


Fig. 3-8: Variation of film thickness along cylinder axis

FIGURE 3



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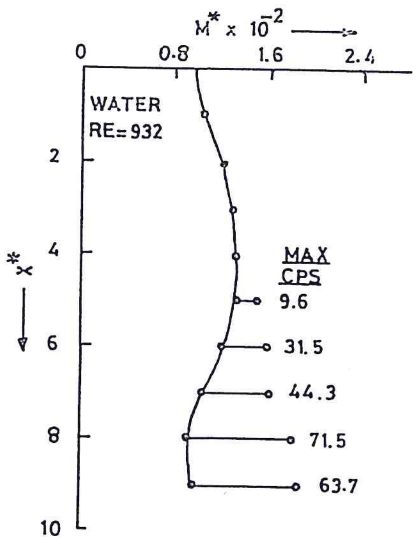

FIGURE 5

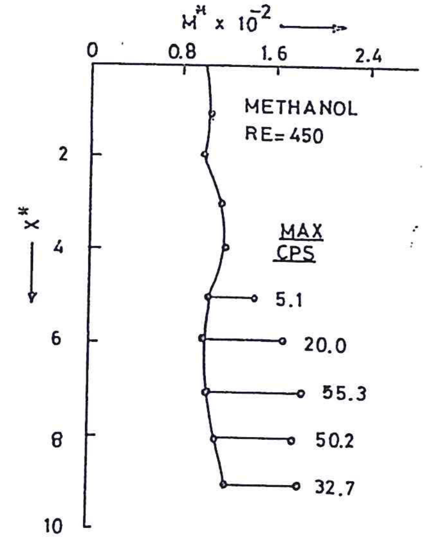

FIGURE 6

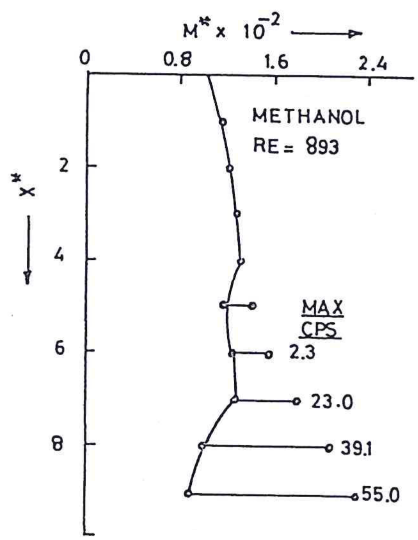

FIGURE 7

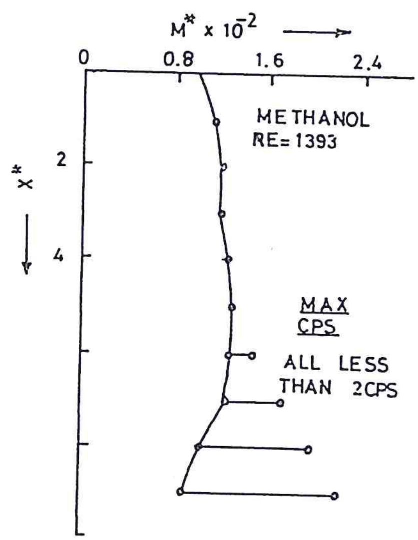

FIGURE 8

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