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CAVITATION IN A LIQUID BETWEEN ROTATING ROLLERS

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1. Introduction

Many industries, notably the printing, paper, linoleum, rubber, plastic and steel industries, use a rolling process to form or otherwise treat sheets of various materials (1), (2). This, and related processes also occur in many problems in lubrication, for example when a loaded disc moves against a shoe (4).

The behaviour of liquids in the region of closest approach (the nip) of two rotating cylinders is complicated by the fact that the cylinders are rarely completely immersed in liquid, but are covered by a film of liquid. In order to simplify a complex situation we have followed Banks and Mill (5) in performing experiments on a pair of rollers completely immersed in liquid in a perspex bath (6).

2. Theory of non-cavitating Newtonian flow

The pressure distribution along a line through the centre of the nip and perpendicular to the axes of the rollers is as figure 1 for the immersed case of infinitely-long rollers separated by a very small gap in a Newtonian liquid, according to Banks and Mill (5).

Using the notation,
U_x is the fluid velocity in direction
U_0 is tangential velocity of rollers
p is pressure in the fluid
η is viscosity of fluid
$x_* = \frac{x}{\sqrt{RH}}$ i.e. non-dimensional x

For a nip gap which is small but not negligible compared to the roller radii we have made use of Jeffery's (7) expression for the stream function to derive the following equations

$$\left(\frac{U_x}{U_0}\right)_{y=0} = \frac{1}{2}\left[\frac{3-X^2}{1+X^2}\right]\left[1 - \frac{1}{2}\frac{H}{R} + o\left(\frac{H^2}{R^2}\right)\right]$$

$$(PD)_{y=0} = -4\eta U_0 \frac{\sqrt{RH}}{H^2} \cdot \frac{X}{(1+X^2)^2}\left[1 - \frac{7}{8}\frac{H}{R} + o\left(\frac{H^2}{R^2}\right)\right]$$

where $X = \frac{x}{\sqrt{RH + \frac{H^2}{4}}}$ and $PD = p - p_l$
p = pressure in the fluid
p_l = hydrostatic pressure

According to the above equations the stagnation line occurs at

$$X = \sqrt{3} \quad ; \quad y = 0$$

The true pressure minima lie on the roller surfaces, but the lowest value of pressure along $y=0$, which occurs at $X = \frac{1}{\sqrt{3}}$, is given by

$$PD_m = -\frac{3\sqrt{3}}{4}\eta U_0 \frac{\sqrt{RH}}{H^2}\left(1 + \frac{7}{8}\frac{H}{R} + o\left(\frac{H^2}{R^2}\right)\right)$$

$$\therefore \quad PD_m = -\frac{3\sqrt{3}}{4}\eta U_0 \frac{\sqrt{RH}}{H^2} \quad \text{for } H \ll R$$

If ν = no. of revs per sec, $U_0 = 2\pi R \nu$

and $$PD_m = -\frac{3\sqrt{3}\pi\nu\eta R^{3/2}}{2H^{3/2}} \qquad \text{------------------ (1)}$$

i.e. the pressure drop is inversely proportional to the nip gap H to the power $^{3}/_{2}$.

Rearranging this equation we get

$$\nu = \frac{2PD_m}{3\sqrt{3}\pi\eta R^{3/2}} H^{3/2} \quad \text{------- (2)}$$

Equation (1) enables us to calculate the maximum pressure drop PD_m for any speed of rotation ν if we know the measurable quantities R, H and η.

Furthermore, if we observe the speed of rotation ν at the onset of cavitation we can calculate the maximum pressure drop PD_m for this threshold.

We will call the value of ν for the onset of cavitation, the cavitation threshold speed.

3. Experimental Work

Banks and Mill (5) in 1954 were the first to show that at a certain speed, when negative pressure exists in the liquid, dissolved air appears out of the liquid as bubbles. They used two perspex rollers 2" in diameter in a perspex tank of paraffin. On gradually increasing the speed of the rollers, at a certain threshold speed of rotation a row of bubbles suddenly appear parallel to the axes of the rollers on the outlet side of the nip. These bubbles can be seen quite easily by the eye. They are usually at about the point B, are about a mm. in diameter, and are about 3 mm. apart.

Equation (2) shows that a graph of ν against $H^{3/2}$ should be a straight line through the origin, and measurement of the slope of the line will enable the maximum pressure drop PD_m for the onset of cavitation to be calculated. This assumes that the temperature and hence η are constant.

Banks and Mill (5) did this for medicinal paraffin and castor oil. Figure 2 shows results for BP polybutene-Hyvis 3 taken by V.A. Coveney at Watford College (6). From the slope, the maximum pressure drop for the onset of cavitation came to (2.0 ± 0.1) atmospheres which corresponds to a negative pressure below atmosphere pressure of $-(1.0 \pm 0.1)$ atmospheres.

We will call this negative pressure below atmosphere pressure for the onset of cavitation, the cavitation pressure threshold.

It is of interest to compare the result with the values obtained by Banks and Mill for paraffin and castor oil.

	Viscosity at 25°C. Poise	Cavitation Pressure Threshold. Atmospheres.
PARAFFIN	1.2	-1.0
CASTOR OIL	7.0	-0.8
POLYBUTENE-HYVIS 3	61	-1.0

4. Bubble Trapping

For a spherical bubble to be trapped:
Horizontal forces on the bubble must balance.

i.e. Viscous Drag = "Lateral buoyancy" force due to pressure gradient.

i.e. $$2\pi\eta r_{trap} C_d U_x = \frac{4}{3}\pi r_{trap}^3 \frac{\partial p}{\partial x} \qquad (3)$$

where C_d is a drag coefficient between 2 and 3.

For a given value of r_{trap}, (3) determines the positions at which the bubble will be trapped. At the stagnation line $U_x = 0$ but $\frac{\partial p}{\partial x} > 0$. Therefore bubbles will not be trapped exactly at the stagnation line, but on the nip side of it.

5. Nuclei

The origin of the bubbles is still a mystery. The most likely idea at the moment is that of Harvey's (8), that they originate from small pockets of air in pits or crevices in the solid surfaces inside the tank, or in particles within the oil. The liquids considered wet perspex i.e. they are oleophilic, so that such a pocket of air would have a curvature indicated in Figure 3, growing as the pressure decreased.

6. Conclusions

Three liquids require a maximum pressure difference of about two atmosphere for bubbles to form on the outlet side of the nip between two rotating rollers immersed in a liquid. The bubbles are trapped at points of hydrodynamic equilibrium. The origin of the bubbles is obscure.

7. Work in Progress

(a) We are now using high-speed photography to study the cavitation nucleation from the roller surface using perspex, steel and aluminium rollers with varying surface finishes.

(b) We are also using high-speed photograhy to study individual bubble growth and shape from the region of the nip to bubble collapse.

(c) We are planning to find out if cavitation occurs in opaque liquids such as printing inks. This involves devising a non-visual method of detecting the bubbles. The method which we hope to employ uses the discovery that at the onset of cavitation there is about a $1^{o}C$ fall in temperature probe connected to a chart recorder.

8. Glossary of terms

- η viscosity
- H nip gap (minimum separation of rollers)
- $o(\frac{H}{R})$ terms of order of $\frac{H}{R}$
- PD pressure difference (relative to hydrotatic pressure) due to hydrodynamic flow)
- PD_m maximum PD
- p pressure
- x distance ⊥ to y and z
- y ⊥ distance from plane of symmetry in the nip gap ($y=0$ midway between rollers)
- z distance along roller axes
- $X = \frac{x}{\sqrt{RH+\frac{H^2}{4}}}$
- r bubble radius
- r_{trap} bubble radius for which drag equals lateral buoyancy
- R radius of rollers
- ν frequency of rotation of rollers
- U_o tangential velocity of rollers
- U_x fluid velocity in direction

9. References

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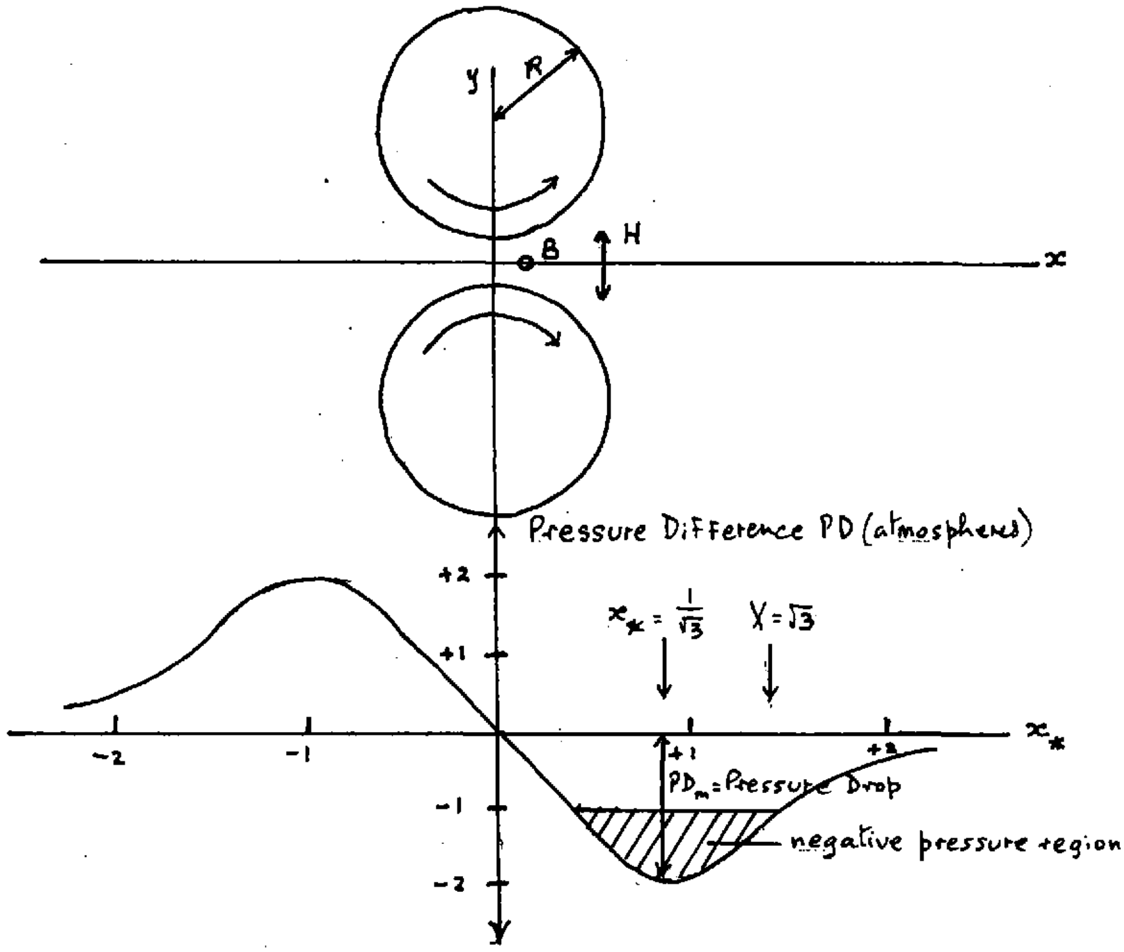

Figure 1 Pressure Distribution through the Nip.

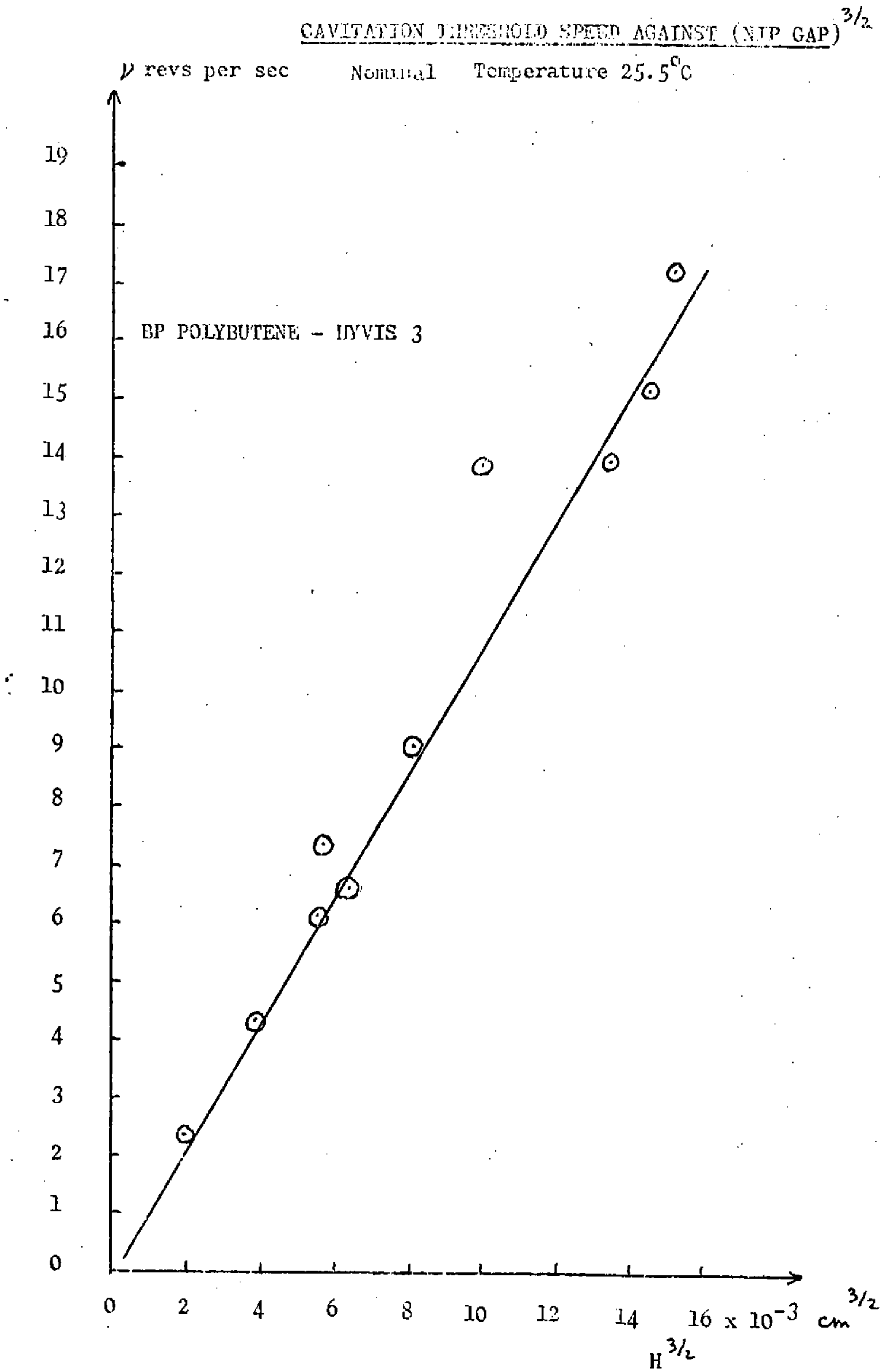

Figure 2 Graph of Frequency of Rotation against (Nip Gap) $^{3}/_{2}$

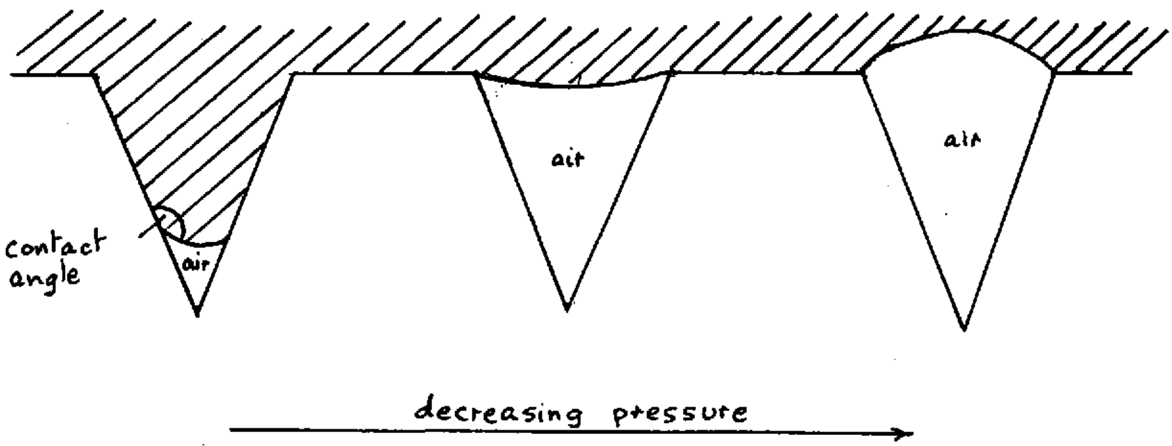

Figure 3 Growth of a Bubble.

DISCUSSION

Dr. Young showed a demonstration of bubble-formation on the outlet side of the nip, using an equipment similar to that originally used by Banks and Mill. The rollers were perspex cylinders about 2 inches diameter operating with a small nip-gap in viscous oil (viscosity about 60 Poises). A magnified image of the region around the nip was projected on to a screen. When the rollers were rotated by hand, a row of bubbles formed on the outlet side (i.e. the low-pressure region). These were of remarkably uniform size, about 0.5 mm diameter and equally spaced (2-3 mms apart). They were aligned parallel to the cylinder axes and a few mms on the outlet side from the point of closest approach. It was not clear why the bubbles grew to a preferred size with regular spacing. It seems to suggest that the original nuclei are within a narrow size-range. But the size-distribution of the nuclei has apparently not been measured.