Int. J. Multiphase Flow Vol. 11, No. 1, pp. 51–62, 1985
Printed in the U.S.A.

0301-9322/85 $3.00 + .00
Pergamon/Elsevier

THE FLOW OF THIN LIQUID FILMS AROUND CORNERS

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(*Received* 12 *October* 1983; *in revised form* 26 *April* 1984)

Abstract—Situations arise where it is required to strip a moving liquid film from a boundary wall. The need to sample wet steam isokinetically is one such situation. Equally it is sometimes desirable for a film not to separate from a boundary wall as in, for example, liquid separators. A theoretical analysis is developed to examine the radial stress distribution within a uniformly thin liquid film flowing around a sharp bend of fixed radius. The results of the analysis are discussed in the light of experimental observations. The controlling parameters in the film flow are identified and are evaluated for a given situation.

INTRODUCTION

The behaviour of thin liquid films flowing over solid surfaces has been the subject of numerous investigations over the last twenty years or so. Consideration has been given to gravity driven films (Mikielwicz & Moszinski 1976), shear driven horizontal films (Murgatroyd 1965), and vertical films with counter and co-current gas streams (Hammitt *et al.* 1976). Various surfaces have been considered including adiabatic, heated, flat, circular and rough surfaces (Hartley & Murgatroyd 1964; Zuber & Staub 1966; Hewitt & Lacey 1965; Wurz 1975.)

The purpose of all this research has been to provide information regarding the behaviour of liquid films whilst flowing over heat transfer surfaces in, for example, condensers and film evaporators. The development of the water cooled reactor has been the principal reason for the abundance of material concerning annular two phase flow. The incentive for the present research described in this paper was provided by the need to strip water film from the wall of steam main prior to isokinetic sampling for steam quality.

In an attempt to sample a wet steam flow Ryley & Holmes (1973) employed a circumferential stripping device to re-entrain liquid previously deposited on the wall of a pipe in order to provide a representative sample of liquid and vapour for isokinetic withdrawal. It was hoped that the liquid would be stripped from the surface by its failure to negotiate the trace circle occurring at the inter-penetration of a cone and cylinder, i.e. at the entrance to a venturi throat. It was believed that liquid accelerating on the converging conical surface would be projected clear of the surface when subjected to the abrupt change of direction. It was found, however, that only about 20% of the liquid known to be originally in the film was entrained. Allowing for any deposition between the throat entrance and the sampling tube it was nevertheless clear that most of the liquid negotiated the sharp edge and continued its progress as a film.

To obtain a better understanding of this phenomenon Parker & Cheong (1973) constructed an apparatus also consisting of a venturi cone followed by a parallel throat. Water was introduced upstream to the walls through a sinter and air was used as a stripping fluid. The throat section was transparent to permit viewing and the entrainment rate was estimated by collecting and weighing the unentrained liquid. They found, for an air Reynolds number of 6×10^4

$$\text{Fractional entrainment} = \frac{K_1}{\dot{m}} + K_2\dot{m}^{0.5}$$

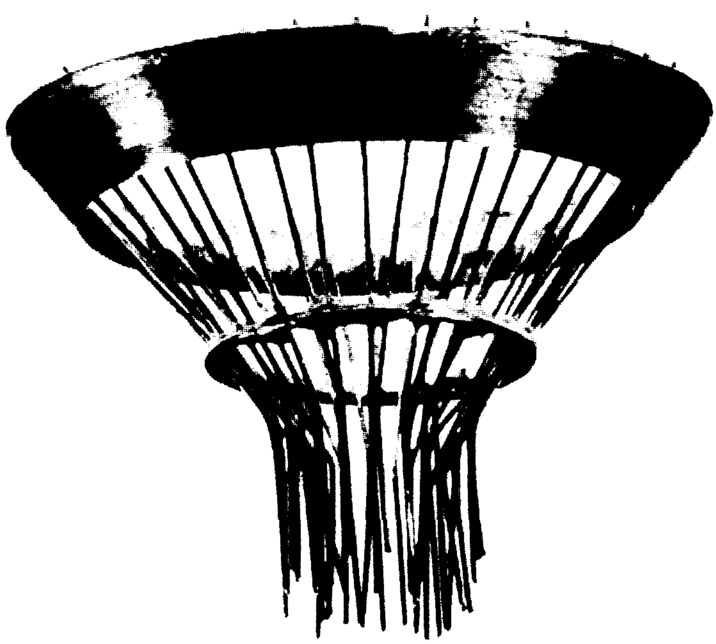

Figure 1. "Wire Thimble" for stripping film from venturi throat.

where $\dot{m}$ was the injected water mass flow rate and K_1 and K_2 were constants for given air flow conditions. The conclusions obtained with steam by Ryley and Holmes were confirmed, viz. the fractional entrainment never exceeded 0.25 and for most values of film flow was about 0.1.

In an attempt to improve the entrainment rate Bensal (1972) devised a number of different designs of wire "thimble" one of which is illustrated in figure 1. This thimble was inserted in the upstream end of the throat of the apparatus described by Ryley & Holmes. The idea was that surface water which might negotiate the bend without entrainment would be enticed downstream along each wire by surface tension, would reach the core of the flow, and then be unable to avoid entrainment. The device was found to improve noticeably the fractional entrainment but was not considered sufficiently promising to pursue further.

If the conical approach surface is made non-wetting the film may be expected, if thin, to break down into rivulets. In this event the adhesion area per unit mass of liquid in transit is reduced and the entrainment rate may be expected to improve. This possibility was tested by Sack (1974) and his results proved inconclusive. It is believed that the non-uniform distribution of entrained drops resulting from rivulet fracture impeded correct sampling by the isokinetic probe.

All our experience of attempting to entrain liquid by subjecting it to a sudden change of direction suggests that films have great tenacity for surfaces and strongly resist displacement. Most stripping devices which impede the movement of a film along a surface reduce to the case where two surfaces interpenetrate at an angle, frequently acute, having a very small radius at the intersection.

A fair amount of practical work on stripping devices has been published from Russian sources. Thus Mostafin (1950) and Suzharev (1950) both used a stripping device which consisted of a series of sharp-edged rings arranged flow-wise around the interior of a pipe conveying a steam/water mixture, their function being to promote re-entrainment of liquid flowing along the inner wall prior to sampling with an isokinetic slotted probe. This device is described in several later Russian papers and referred to as the "TSKT1" steam intake pipe/mixer. Alenchikov *et al.* (1956) presented results of tests using this device. They also presented results from a "BPK" steam intake pipe/mixer which is similar in principle, but for a stripper it employs a venturi type cone followed by a parallel throat and diffuser leading to a single nipple isokinetic probe. Mozharov & Panasenko (1959), using salt as a tracer, investigated the performance of the BPK equipment.

None of the above were concerned with the nature of the stripping process; they reported the results of tests but attempted no analysis. Mozharov (1959) studied experimentally the stripping of liquid from the inner wall of a pipe unimpeded by a stripping device, but again, no analysis was offered.

Two phase annular flow in branched pipe networks is another application where it is necessary to dislodge the liquid from the pipe wall. In this case the purpose is to avoid the situation where the vapour phase will negotiate the bend into a branch line whilst the bulk of the liquid remains in the main pipeline. In a complex network this repeated liquid separation will lead to some locations receiving essentially dry vapour with other locations receiving just liquid. This case has been investigated by Fouda & Rhodes (1974) where they used baffles and orifices as homogenisers. Whilst the aim of these devices is similar to those used for sampling the result of holding up the flow will cause non-uniform stripping, with respect to both space and time (Sekoguchi *et al.* 1978). This situation, therefore, does not easily lend itself to analysis.

Circumstances also exist where it is important that the liquid film does not separate from the surface, for example, in liquid separators. In either case, an insight into the film behaviour can be given by examining the forces acting on the film as it turns the corner. This paper describes an analysis of the radial stress distribution within a simplified thin liquid film flowing around a sharp corner. An attempt is made to evaluate the results of the theory in the light of experimental observations.

THEORETICAL ANALYSIS OF A LIQUID FILM FLOWING AROUND A CORNER

Consider the two-dimensional flow of a liquid film, of uniform thickness, h, around a corner of radius, R_1, figure 2(a). The actual velocity profile within the film will depend on a number of factors. Turbulent and laminar films have different velocity profiles as do gravity-driven and shear-driven films. If counter or co-current gas streams are present the

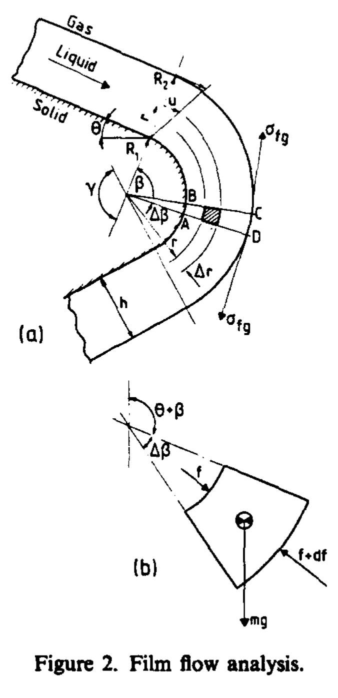

Figure 2. Film flow analysis.

velocity profiles in the film will again be different. The following analysis can be pursued assuming the relevant film velocity profile. In this paper two particular kinds of film flow will be considered:

(a) *Shear-driven laminar film*

For this situation, where the weight of the liquid is not significant, the velocity u at a distance y from the surface is given by:

$$\frac{u}{\bar{U}} = \frac{2y}{h}$$

where $\bar{U}$ is the mean film velocity (figure 2).

In terms of the geometry of the bend

$$\frac{u}{\bar{U}} = \frac{2(r - R_1)}{(R_2 - R_1)} \qquad [1]$$

(b) *Gravity-driven laminar film*

Here the velocity profile is represented by:

$$\frac{u}{\bar{U}} = \frac{3}{2h^2}(2yh - y^2)$$

or

$$\frac{u}{\bar{U}} = \frac{3[2(R_2 - R_1)(r - R_1) - (r - R_1)^2]}{2(R_2 - R_1)^2} \qquad [2]$$

where

$$\bar{U} = \frac{1}{h}\int_0^h u \, \mathrm{d}y. \qquad [3]$$

Consider an element at a radius r within the segment $ABCD$ which subtends an angle $\Delta\beta$ at the centre and has a unit depth, figure 2(b). Compressive stresses, f, are acting in the radial direction. Applying Newton's second law to the element:

$$(f + \mathrm{d}f)(r + \mathrm{d}r)\Delta\beta - fr\Delta\beta - mg[-\cos(\theta + \beta)] = m\frac{u^2}{r}. \qquad [4]$$

The mass of the element is given by:

$$m = \rho r \Delta\beta \, \mathrm{d}r \qquad [5]$$

where ρ is the density of the liquid.

Expanding[4] and including [5] gives:

$$f + r\frac{\mathrm{d}f}{\mathrm{d}r} = \rho u^2 - \rho g r \cos(\theta + \beta)$$

or

$$\frac{\mathrm{d}}{\mathrm{d}r}(fr) = \rho u^2 - \rho g r \cos(\theta + \beta) \qquad [6]$$

For the sake of clarity the following analysis and discussion will be based on a shear-driven film represented by [1].

Therefore, assuming $\bar{U}$ to be constant throughout the bend, [6] becomes:

$$fr = \int \left\{ 4\rho \left[\frac{r - R_1}{R_2 - R_1} \right]^2 \bar{U}^2 - \rho g r \cos(\theta + \beta) \right\} \mathrm{d}r. \qquad [7]$$

Integrating this expression with the boundary condition at $r = R_2, f = 0$ (i.e. there are no inertial or gravity forces at the surfaces) gives:

$$f = \frac{4\rho\bar{U}^2}{r(R_2 - R_1)^2} \left\{ \left(\frac{r^3}{3} + R_1{}^2 r - R_1 r^2 \right) - \left(\frac{R_2{}^3}{3} + R_1{}^2 R_2 - R_1 R_2{}^3 \right) \right\}$$
$$- \frac{\rho g \cos(\theta + \beta)}{2r} \{r^2 - R_2{}^2\}. \qquad [8]$$

Equation [8] describes the radial compressive stress, f, in the segment ABCD due to its inertia and weight as it negotiates the bend. Superimposed upon this value is a further radial compressive stress, f_s, due to the surface tension, σ_{LG}, acting in the curved film surface. This additional stress will be independent of r and will be uniformly transmitted through the film around the bend. From figure 2(a).

$$f_s R_2 \Delta\beta = 2 \sin\left(\frac{\Delta\beta}{2}\right) \sigma_{LG}$$

or, as $\Delta\beta \to 0$

$$f_s = \frac{\sigma_{LG}}{R_2}. \qquad [9]$$

Therefore, the distribution of the total radial compressive stress through a shear-driven film as it flows around the bend is:

$$F = \frac{4\rho\bar{U}^2}{r(R_2 - R_1)^2} \left\{ \left(\frac{r^3}{3} + R_1{}^2 r + R_1{}^2 t - R_1 r^2 \right) - \left(\frac{R_2{}^3}{3} + R_1{}^2 R_2 - R_1 R_2{}^2 \right) \right\}$$
$$- \frac{\rho g \cos(\theta + \beta)}{2r} \{r^2 - R_2{}^2\} + \frac{\sigma_{LG}}{R_2}. \qquad [10]$$

The three components on the r.h.s. of [10] are due to the inertial (centrifugal) force, the gravity force, and the surface tensile force, respectively. The inertial and surface tensile terms are dependent on the film properties and the fixed geometry of the bend. The gravity term, however, is also a function of the orientation of the bend and the angle through which the film has turned. It is both convenient and practical to consider the extreme effects of gravity, i.e. to consider the cases when gravity assists the film in negotiating the bend and when gravity impedes it from doing so. This is achieved by setting $(\theta + \beta)$ in [10] to 0 and 180°. Assuming these values does not give the corner a fixed orientation but does fix a position in the film with regard to the direction in which gravity will act.

From [10] it is possible to identify four parameters which will influence the radial stress distribution in the film as it flows around the corner. These are: (a) the film mean velocity, $\bar{U}$; (b) the bend radius, R_1; (c) the film thickness, $h = R_2 - R_1$; (d) the liquid properties, ρ and σ_{LG}, which can be conveniently varied by considering different liquid temperatures.

In practical circumstances it is clear that other factors will be involved, for example, the presence of disturbances on the film surface and local thickening due to a meniscus at the boundary. In the presence of large interfacial shear stresses the film surface will become wavy, the aerodynamic drag on these waves may cause stripping and some of the liquid will be entrained into the gas flow. However, in view of the poor performance achieved by stripping devices it is clear that this mechanism does not lead to high liquid entrainment rates and that the bulk of the film will remain attached to the surface. These, and other unpredictable factors cannot be allowed for, but they can be borne in mind when observing the behaviour of a real film.

Figure 3 shows the radial compressive stress distribution in a 1 mm shear-driven water film at 20°C flowing around a corner of radius 1 mm for three different values of $\bar{U}$. A net compressive stress (i.e. a positive stress in the sign convention adopted) means that the forces present are acting to maintain the film flowing around the corner. For the lower velocity the film is in compression throughout. As the film velocity is increased, however, it can be seen that the stress towards the inside of the bend becomes tensile as the inertia term in [10] increases. At the liquid/gas interface the stress is due only to the surface tension and therefore has a value common to all film velocities since the overall geometry remains the same.

Figure 4 describes the effect of the corner radius on the radial stress distribution in the water film. It can be seen that whilst the sharper bend increases the compressive stress near the surface due to the enhanced surface curvature, it also causes an increase in the tensile stress on the inside of the bend due to the greater inertial (centrifugal) force. It is interesting to note that for the 5 mm corner radius where gravity is acting to maintain the film around the bend that the minimum stress does not occur at the solid surface. This is because in this particular case, the large radius causes a low inertial force. In figure 5 it can be seen that a thicker film also promotes a tensile stress and that as the film becomes thicker so the relative magnitude of the gravity force increases. The final effect considered is that of

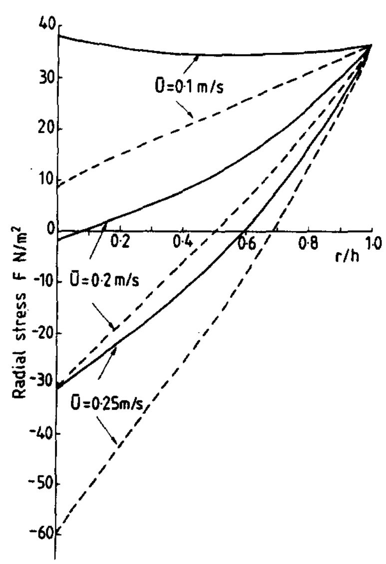

Figure 3. Effect of film velocity on radial stress distribution. Water temperature = 20°C; film thickness = 1 mm; Corner radius = 1 mm; ———, gravity assisting film attachment; ------, gravity opposing film attachment.

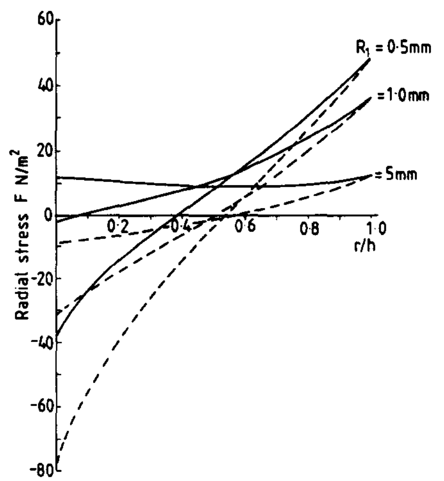

Figure 4. Effect of corner radius on radial stress distribution. Water temperature – 20°C; mean film velocity = 0.2 m/s; film thickness = 1 mm; ———, gravity assisting film attachment; ------, gravity opposing film attachment.

the liquid temperature, figure 6. Raising the water temperature has the combined effects of reducing the surface tension and hence the associated force and of simultaneously decreasing the liquid density and thus the inertial and gravity forces. The overall effect of increasing the liquid temperature is to reduce the compressive stress in the film since the surface tension is the stronger function of temperature.

Figures 3–6, therefore, describe the effects on the film radial stress distribution of the parameters listed in (a)–(d) above. If the film is in compression throughout its thickness then there is no doubt that it will negotiate a corner. If the film is in tension, however, this does not necessarily mean that it will fail in negotiating the corner. There are strong adhesive forces acting between the solid surface and the liquid on a molecular scale. Within the liquid itself there are slightly weaker, but nevertheless very strong, forces of cohesion acting. Liquid can sustain a considerable degree of tension. It has been shown in special circumstances that clean water can sustain a tensile stress up to 0.34 MN/m² (Ryley 1979); this suggests that the liquid might cavitate before the stress is sufficient to break the molecular bonds. Returning to the real situation, however, where further disturbing influences will act, the fact that the film is in tension means that if it does separate from

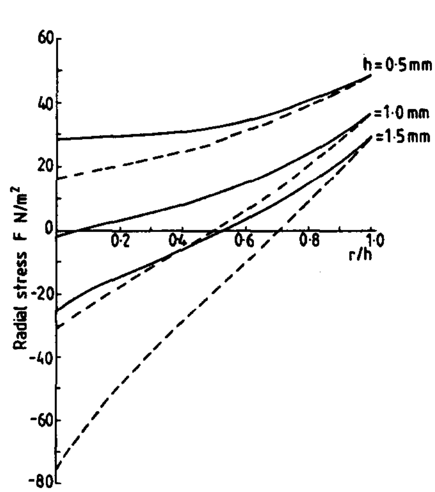

Figure 5. Effect of film thickness on radial stress distribution. Water temperature = 20°C; mean film velocity = 0.2 m/s; corner radius = 1 mm; ———, gravity assisting film attachment; ------, gravity opposing film attachment.

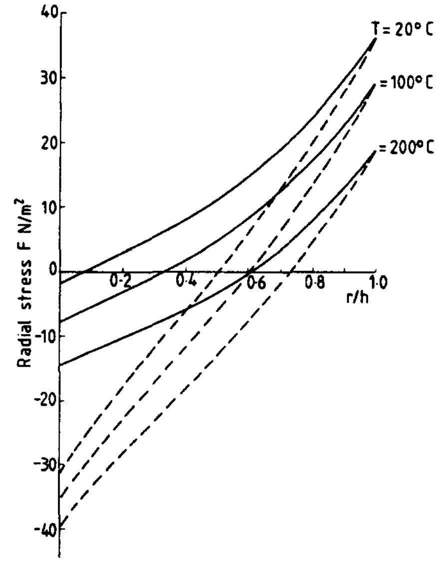

Figure 6. Effect of film temperature on radial stress distribution. Mean film velocity = 0.2 m/s; film thickness = 1 mm; corner radius = 1 mm; ———, gravity assisting film attachment; – – – – – –, gravity opposing film attachment.

the corner it should not re-attach. Furthermore, the general trend seen in figures 3–6 shows that the maximum tension occurs at the solid boundary, i.e. if the film is to separate it will do so at the wall. However, such a situation is not quite realistic. For wetting surfaces, the adhesive forces between the wall and the liquid are very difficult to overcome and it is more likely that the film will break just within the liquid leaving a very thin layer of liquid on the wall. This thin layer will probably build up with time and be re-entrained into the separated liquid through the meniscus thus formed. If the tensile stresses within the separated film are not very great, then observations show that the film can re-attach. There appear to be two causes of this: firstly, the surface tension between the solid wall and the separated film, and secondly, the aerodynamic forces which occur due to the proximity of the solid wall and the moving fluid, similar to the forces that produce the Coanda effect. It might be worth making the point here that the ability of a thin film to negotiate a sharp bend is very different from the Coanda effect. When a jet flows close to a diverging boundary wall, the entrainment of fluid from the restricted area between the jet and the wall causes a local pressure reduction. The pressure differential across the stream moves it closer to the boundary wall causing yet a further fall in the local pressure. This process causes the jet to attach itself to the boundary wall. The Coanda effect does not depend on surface tension but on fluid-dynamic forces. The jet can be submerged, i.e. have no surface, and can be a gas.

The previous discussion is equally applicable to the case of a gravity-driven film negotiating a sharp corner. Figure 7 shows a comparison between the radial stress distribution within a shear-driven and a gravity-driven film. The stress distribution within the gravity-driven film can be found by solving [7] using the velocity profile of [2]. Whilst figure 7 shows that the stress distribution in the film is dependent on the velocity profile, the general features are nevertheless the same.

By realising that the film will theoretically separate at the wall it is possible to re-arrange [10] to represent this situation by putting $r = R_1$. If F_w is the radial compressive stress at the wall, then:

$$F_w = 4\rho \bar{U} \frac{2(R_1 - R_2)}{3R_1} - \frac{\rho g \cos(\theta + \beta)(R_1^2 - R_2^2)}{2R_1} + \frac{\sigma_{LG}}{R_2} \qquad [11]$$

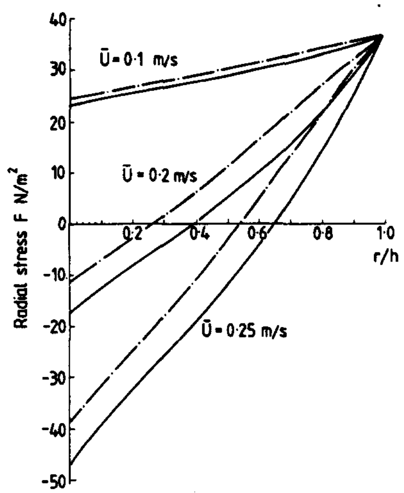

Figure 7. Effect of film velocity profile on radial stress distribution. Water temperature = 20°C; film thickness = 1 mm; corner radius = 1 mm; ———, linear velocity profile (shear-driven film) —·—, parabolic velocity profile (gravity-driven film).

Solving [11] for $F_w = 0$ leads to a relationship between the film velocity and the film thickness for a particular corner radius. A horizontal shear-driven film negotiating a right-angled bend can be represented in [11] by putting $(\theta + \beta) = 0°$, such that the gravity component is assisting the film in negotiating the bend. A vertical gravity-driven film can also be represented by developing an equation similar to [11] but based on [2]. Putting $(\theta + \beta) = 180°$ in this equation represents the situation where the film is flowing vertically downwards towards a right-angled bend such that gravity is now acting to prevent the film negotiating the corner. Figure 8 shows a graphical representation of the parametric limits which will permit the film to negotiate the bend. The lower curve represents the gravity-driven film and has been calculated for water at 20°C whilst the upper curve, representing the horizontal shear-driven film, has been calculated for water at 55°C. The reason for this is to permit a convenient comparison with experimental data. There is not a significant difference between the calculated values for water at 20°C and water at 55°C.

Superimposed on the parametric limitations that have been identified there are further practical constraints. In the case of the gravity-driven film two practical constraints can be identified. Firstly, it is not possible to produce a thick film which is flowing only slowly

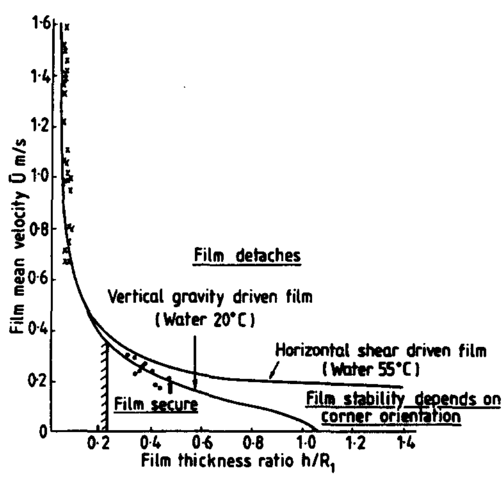

Figure 8. Critical film flow around 1.5 mm radius corner. ———, theoretical curve; *X*, experimental data for horizontal shear-driven film; ●, experimental data for vertical gravity-driven film; ⫿ minimum film thickness of gravity driven film (Mikielewicz and Moszynski 1976).

under the influence of gravity, and secondly, there is a minimum thickness of a liquid film below which capillarity causes it to rupture. This latter constraint, as evaluated by Mikielewicz & Moszynski (1976), can be seen in figure 8. This corresponds to a non-dimensional critical film thickness h^+ of 0.8, where

$$h^+ = \left(\frac{\rho^3 g^2}{15\,\mu^2 \sigma_{LG}}\right)^{1/5} h.$$

Practical constraints can also be identified for the horizontal shear-driven film. As in the previous situation there is a minimum film thickness before it breaks down; this is a function of the film velocity and of the interfacial shear stresses from the gas stream which are necessary to propel the film. A second constraint is imposed by the requirement of a tranquil surface. Van Rossum (1959) experimentally evaluated the limiting gas velocity above which surface waves are produced. For example he found that for a 1 mm thick swept water film the maximum air velocity was about 5 m/s, above this value surface waves were generated.

EXPERIMENTAL INVESTIGATION OF A THIN WATER FILM FLOWING AROUND A CORNER

Equation [10] describes the radial stress distribution in a thin liquid film flowing around a corner. It is not possible to test experimentally this equation. The special case described by [11] however, can be tested. Figure 9 shows the experimental arrangement that was devised to test the lower curve in figure 8. A thin film of tap water having a temperature of 20°C was allowed to flow down a prepared channel on a vertical surface towards a right-angled bend having a 1.5 mm radius. The meniscus which formed at the sides of the channel was removed using guide wires. The water flow rate was reduced until the film just managed to negotiate the bend. After turning the bend the water was guided into a measuring cylinder where it was collected over a measured period of time. The film thickness before the corner was measured using a micrometer arrangement.

Some of the experimental results obtained are included in figure 8. There is inevitably some scatter in the data because of the metastability of the film flowing around the bend due to the external influences discussed in the previous section. Also it was not possible to gain data for slower moving relatively thick films since the two requirements are mutually incompatible.

The case of a horizontal shear-driven film negotiating a 1.5 mm radius bend was investigated using a specially prepared low pressure steam tunnel, figure 10. The water was driven, by the shearing action of the steam flow, along a horizontal flat plate instrumented with thermocouples and conductance film thickness probes. The water temperature was maintained at 55°C ± 2°C throughout the experiment. The results obtained are included in

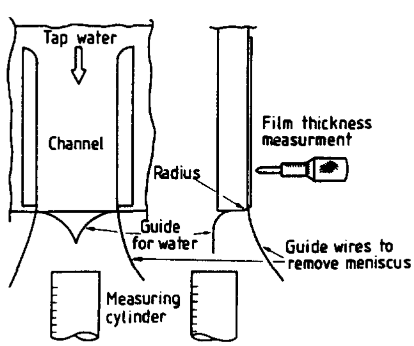

Figure 9. Apparatus for gravity driven film flowing around a corner.

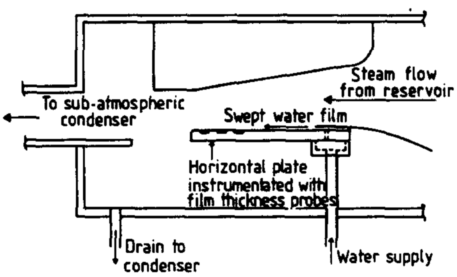

Figure 10. Low pressure steam tunnel for horizontal film flow around a corner.

figure 8. It can be seen that all the data is for quite thin films (0.125 mm > h > 0.075 mm). It proved impossible to produce a suitable thicker, slower moving film using the apparatus described in figure 10.

For both the vertical and horizontal film flows there is a definite threshold velocity above which the film fails to negotiate the bend. It can be seen from figure 8 that the theoretical prediction of this velocity is reasonably accurate. It can also be seen that for thicker films, $h/R_1 > 1.06$, it is the gravity term which determines whether or not the film successfully negotiates the bend.

CONCLUSION

Situations arise where it is required to strip a liquid film from a boundary wall. The need to sample isokinetically wet steam flows is one such situation. Equally it is sometimes desirable that a film does not separate from a boundary wall as in, for example, liquid separators. Equally it is sometimes desirable that a film does not separate from a boundary wall as in, for example, liquid separators. Practical experience shows that to remove totally a water film from a surface can be very difficult. It is common sense that a thick, fast moving film will fail to negotiate a sharp bend as in, for example, a pouring spout. It is not so obvious, however, whether or not a thin film will successfully negotiate a sharp bend. A theoretical analysis has been developed to examine the radial stress distribution within a uniformly thin liquid film flowing around a corner having a fixed radius. The analysis and the discussion presented herein have attempted to clarify the controlling parameters and to quantify them for given situations.

The surface tension within the curved film surface as it flows around the bend provides the compressive stress necessary to hold the film to the boundary wall. The inertia (centrifugal) force within the liquid acts to cause the film to leave the wall. The effect of gravity depends on the orientation of the film and of the bend. The criteria assumed for film separation is the presence of a tensile stress within the liquid. It has been recognised that liquids can sustain tension, but nevertheless the presence of a tensile stress means that once the film has separated due to commonly occurring disturbances it will probably remain separated. It has also been shown that the theoretical point of separation is the boundary wall. The theoretical analysis agrees well with experimentally obtained results.

Acknowledgements—The work reported herein was carried out in the Heat and Mass Transfer Laboratory at the University of Liverpool.

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