9th AUSTRALASIAN
FLUID MECHANICS CONFERENCE,
AUCKLAND, 8-12 DECEMBER 1986

Stability of Liquid Coating in the Jet Stripping Process

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ABSTRACT

The study of surface stability of thin liquid film is of great importance in strip coating processes since the quality of the solidified surface is often influenced by the surface wave formation on the coating in its liquid state. This paper discusses a first order perturbation solution to the Orr-Sommerfeld equation for a thin viscous film under the influence of external forces and surface shear stresses, in addition to gravity and surface tension effects.

The solution is then applied to the jet stripping process of the continuous hot dip metallic coating lines. It is found that waves originating from disturbances at regions above and below the critical stripping point would propagate along and opposite to the direction of the strip movement respectively. In addition, waves of wavelength over a certain value, depending on the stripping conditions, are found to grow near the critical stripping position, with attenuation effects observed only at a distance sufficiently further downstream from it.

INTRODUCTION

In many industrial applications, the coating of a thin film is required to be applied on to a surface such as for sacrificial protection of the substrate in steel strip galvanizing. In this process, a continuous strip of material is dragged vertically from a bath of coating liquid with a constant velocity and the final thickness of the coating is usually controlled either by coating rolls or by the application of an external pressure and a shear stress field using air knives, referred to as 'jet stripping'.

Coating rolls in hot dip galvanizing lines were widely used from the late 1930s to the 1970s but have been gradually replaced by the later method in coating thickness control due to various advantages of the latter (see, for example, Butler et al, 1970). The coating thickness variation in hot dip galvanizing using air knives has been studied by many workers both empirically (Nikoleizig et al, 1978, Adaniya and Shoji, 1980) and theoretically (Thornton and Graff, 1976; Ellen and Tu, 1983; Tuck and Vanden Broeck, 1984; Ellen and Tu, 1984). In the calculation of the film thickness distribution along the strip, the effect of surface tension is found to be negligible (Ellen and Tu, 1984) and the mean flow described by Ellen and Tu, 1983, which included the important effect of surface shear stress in the analysis, will be used here in studying the surface wave instability of the liquid coating on the strip surface.

It is in no doubt that the surface appearance of the finally solidified coating film is closely related to the stability of the coating film in its liquid state. An understanding of the relevant parameters governing the mechanism of the film's formation is essential for the continued development and improvement of the process and should lead to a solution in controlling the formation of waves on the strip surface.

The instability of a thin liquid film with a free surface has been a subject of extensive study and has been investigated by many workers, see, for example, stability studies of thin film flowing down an inclined surface by Yih, 1973; Lin, 1967; Bach and Villadsen, 1983; Goussis and Kelly, 1985; and instability investigation of sheared liquid layers on a stationary surface by Miles, 1960; Smith and Davis, 1982.

The relevant stability problem to be discussed here is that of a flow with a mean flow profile described by Ellen and Tu, 1983, and a solution for the wave speed and amplification factor is sought. A perturbation solution to the Orr-Sommerfeld equation will be discussed and it will be used to examine the importance of the variables involved in controlling instability of the coating film in continuous hot dip galvanizing. A more elaborate discussion of the problem is given by Tu et al, 1986.

STABILITY ANALYSIS

Consider an isothermal incompressible thin film of thickness h, having a parabolic mean velocity profile and bounded by a solid wall which moves vertically with a constant velocity U_o. The film is assumed to be Newtonian with a constant viscosity, density and surface tension. In addition to the gravitational force, the film is subjected to the action of a pressure gradient and surface shear stress as shown in Figure 1(a).

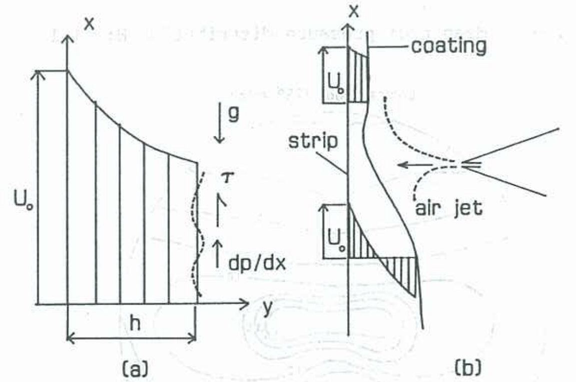

Figure 1 (a) Basic velocity profile; (b) sketch showing the jet stripping process.

For a steady state vertical withdrawal of a flat plate from a viscous fluid bath under the influence of a pressure and surface shear stress imposed by a two-dimensional jet such as in the continuous galvanizing process, Ellen and Tu, 1983, have shown that the mean velocity profile can be conveniently written in the form:

$$\bar{u} = 1-\tfrac{1}{2}\tilde{G}(2-y)\ y + \tilde{S}y \qquad (1)$$

where $\tilde{G} = GT^2$, $\tilde{S} = ST$, $\bar{u}$ is the mean velocity non-dimensionalized with the plate velocity, U_o; y is non-dimensionalized by the film thickness, h. T, S and G are the non-dimensional film thickness, shear stress and effective gravitational acceleration defined by

$$T = h\ (g/\nu U_o)^{1/2},$$
$$S = \tau\ (\mu\rho g U_o)^{-1/2}, \qquad (2)$$
$$G = 1 + (dp/dx)/(\rho g),$$

The gravitational acceleration, liquid density, dynamic and kinematic viscosities are denoted by g, ρ, μ and ν respectively. τ and dp/dx are the surface shear stress and pressure gradient in the x direction.

On this equilibrium flow, a slight perturbation is introduced to the stream function and pressure:

$$\psi = \psi_o + \psi e^{i\alpha(x-ct)},$$
$$p = p_o + pe^{i\alpha(x-ct)}, \qquad (3)$$

where the stream function ψ_o, and pressure p_o correspond to the mean flow, α is the wave number defined by $2\Pi h/\lambda$, λ being the wavelength; $c=c_r+ic_i$, c_r being the wave velocity and αc_i being the rate of amplification or damping; and t denotes the time.

It is noted that the velocity components, x and y, t and ψ are non-dimensionalized by the plate vertical speed U_o, the film thickness h, h/U_o and U_oh respectively.

The continuity condition is satisfied and the velocity components are:

$$u = \partial\psi/\partial y$$
$$v = -\partial\psi/\partial x \qquad (4)$$

By cross differentiation and after linearization of the Navier-Stokes equations, the well-known Orr-Sommerfeld equation is obtained:

$$\psi^{\text{iv}} - 2\alpha^2\psi'' + \alpha^4\psi - i\alpha R\{(\bar{u}-c)(\psi'' - \alpha^2\psi) - \bar{u}''\ \psi\} = 0, \quad (5)$$

where $R=U_oh/\nu$ is the Reynolds number and primes denote differentiation with respect to y.

The boundary conditions at the plate boundary and at the free surface of the liquid film are:

$$\psi = \psi' = 0 \text{ at } y = 0 \qquad (6)$$

$$p_{xy} = \mu(\partial v/\partial x + \partial u/\partial y),$$
$$p_{yy} = -p + 2\mu\partial v/\partial y + \sigma\partial^2 y/\partial x^2, \qquad (7)$$

where σ is the surface tension, p_{xy} and p_{yy} are the tangential and normal stress components at the free surface.

After some manipulations using the regular perturbation method, a first-order solution of c ($c=c_r+ic_i$) is obtained:

$$c_r = 1-\tilde{G} + \tilde{S}, \qquad (8a)$$

$$c_i = \alpha R[2\tilde{G}(\tilde{G}-\tilde{S})/15-N], \qquad (8b)$$

where $N = (1/3)\ \alpha^2\sigma\ /(\rho U_o^2 h)$ corresponds to the surface tension term.

Equation (8a) suggests that the wave speed is independent of wave number and is a function of G, S and T only. On the other hand, the amplification factor c_i is dependent on α and Equation (8b) indicates that the wave is stable when

$$2\tilde{G}(\tilde{G}-\tilde{S})/15-N < 0 \qquad (9)$$

In the special case corresponding to the situation of a thin film on a stationary vertical surface under the influence of gravity only (G=1, S=0 and U_o=0), Equation (8b) degenerates to an amplification factor which is identical to that given by Yih, 1963 and Lin, 1973. In addition, Equation (8a) agrees with the leading term of Lin, 1973 under the same conditions. (It should be noted that the reference velocity used by Yih, 1963, and Lin, 1973 is different from that used in this paper.)

APPLICATION

The above solution for the film stability is now applied to the jet stripping process to examine the surface wave propagation and its stability in strip metallic coating. In the steady state withdrawal of a flat plate from a viscous fluid bath, remote from the meniscus region, external pressure and shear stress fields are imposed by a two-dimensional gas jet impinging on the plate moving at a constant speed which is much less than the air velocity of the jet (see Figure 1(b)). Along the plate at any position x, G and S are known from the knowledge of the jet impingement pressure and the wall shear stress on the plate. It is argued that there is a position x=x*, referred to as the 'critical stripping position', such that the combined effect of G and S is maximum which allows a final withdrawal flux of coating liquid to be determined (Ellen and Tu, 1983). Knowing G(x) and S(x) the strip speed U_o and the basic properties of the coating liquid it is then possible to calculate the coating thickness T, the wave speed and the amplification or damping rate distribution along x.

As an illustration, Figure 2 shows the variation of G, S and T with x/d, where d is the jet slot opening and x is the distance from the stagnation pressure of the jet. In this example, the liquid coating is molten zinc with a density and viscosity of 6540 kg m^{-3} and 0.003 Nsm^{-2} respectively; d=1 mm; U_o=1 m/s; the jet is normal to the strip and is located at a distance of 15 d from the strip and the jet plenum pressure is 16 kPa above ambient. The jet impingement characteristics described by Beltaos, 1976 are used. These line conditions will be used in the calculations for the following sections.

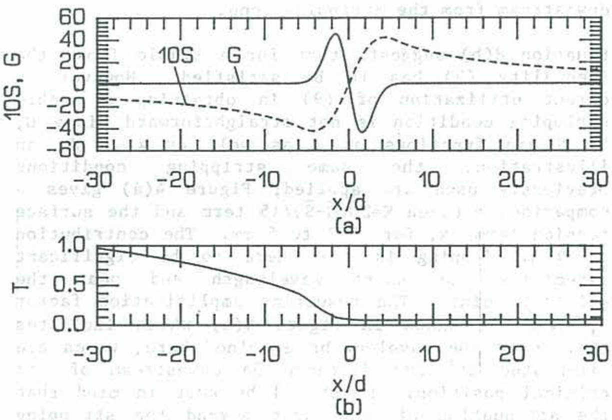

Figure 2 Variation of G, S and T along the plate in the stripping region.

The wave velocity variation is shown in Figure 3(a) which indicates that at the positions downstream from x*, the wave speed increases rapidly and

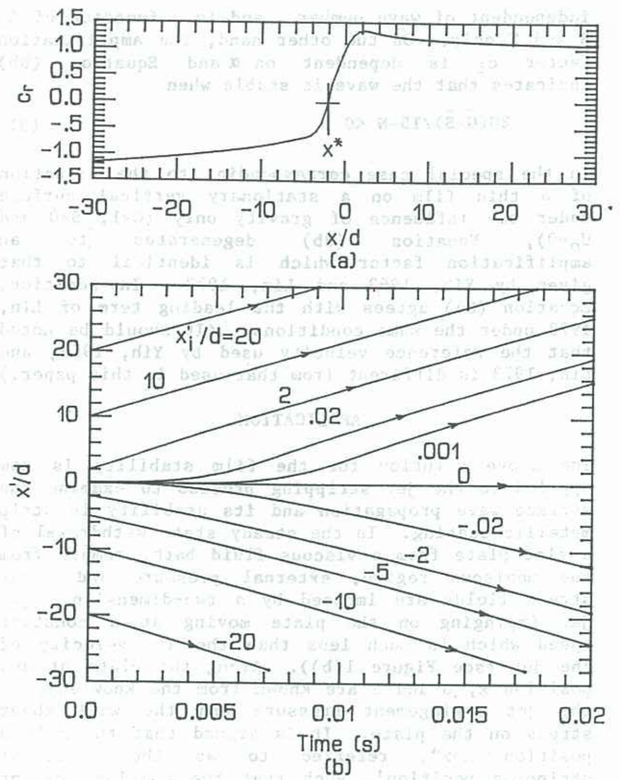

Figure 3 (a) Variation of wave speed along the strip; (b) traces of wave position with time for various starting positions x_i'.

reaches a maximum before it gradually decreases to the strip speed. On the other hand, upstream of the critical position the waves would propagate in the opposite direction toward the liquid bath with a magnitude greater than U_o at positions 15-20 d upstream of x^*. Further illustrations can be found in Figure 3(b) which shows the traces of wave propagation with time at various starting positions x_i' along the strip (x' is defined as $x'=x-x^*$). These traces of disturbances are radiating in opposite directions from the critical position and they suggest that the disturbances of any significance are those originating downstream of x^* since they will travel with the strip until solidification at certain distance further downstream from the stripping zone.

Equation 8(b) suggests that for a stable flow, the inequality (9) has to be satisfied. However, a direct utilization of (9) in obtaining a stable stripping condition is not straightforward since G, S, N are functions of x as well as α. As an illustration, the same stripping conditions previously used are applied; Figure 4(a) gives a comparison between $K=2\tilde{G}(\tilde{G}-\tilde{S})/15$ term and the surface tension term, N, for λ=1 to 5 mm. The contribution of N in damping is seen here to be significant especially for short wavelength and near the critical point. The resulting amplification factor $c_i/(\alpha R)$ is shown in Figure 4(b) which indicates that, over the wavelengths examined here, waves are attenuated at some distance 5d downstream of the critical position. It should be kept in mind that the attenuation of the waves beyond the stripping zone is not always achieved, for example, if the film thickness is large or if the surface tension is sufficiently low, the waves may become unstable. It can be shown that the wave speed is zero at the critical position x^* and disturbances of wave number α such that $\alpha < [2\tilde{G}^*/(5\sigma/\rho U_o h^*)]^{1/2}$ are unstable. For the conditions used in this illustration ($\tilde{G}^*$ and h^* denote the value of $\tilde{G}$ and h at $x=x^*$), at the critical position the waves with

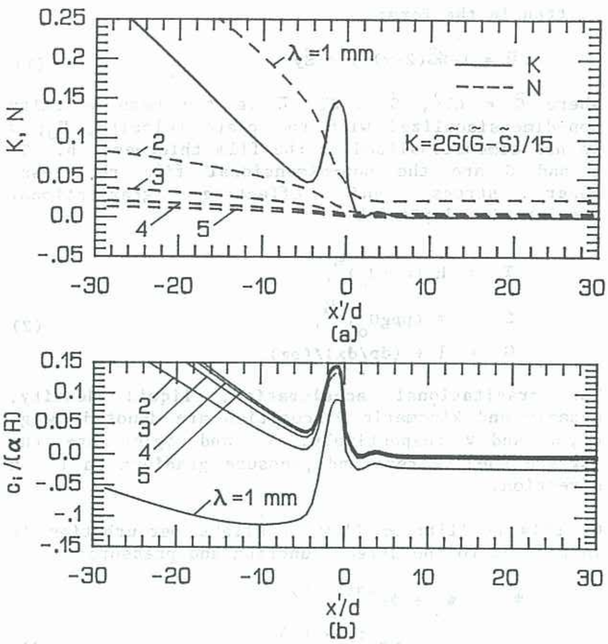

Figure 4 (a) Comparison between the contribution of G, S and surface tension term N; (b) variation of $c_i/(\alpha R)$ with distance for various wavelengths.

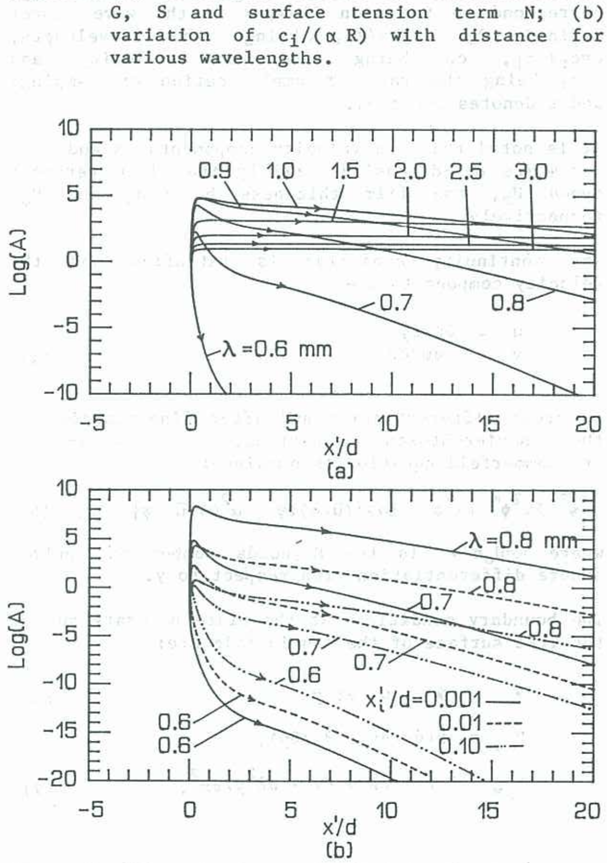

Figure 5 (a) Traces of wave amplitude with distance for various wavelengths (x_i'/d=0.01); (b) traces of wave amplitude at various initial positions x_i' downstream of the critical position.

$\alpha < 0.23$, ie $\lambda > 0.69$ mm, are unstable. However due to the damping effect downstream of the critical position, not all the disturbances would be significant at a long distance downstream beyond the stripping zone.

It is of practical interest to follow a wave of a given initial amplitude (taken as unity in this

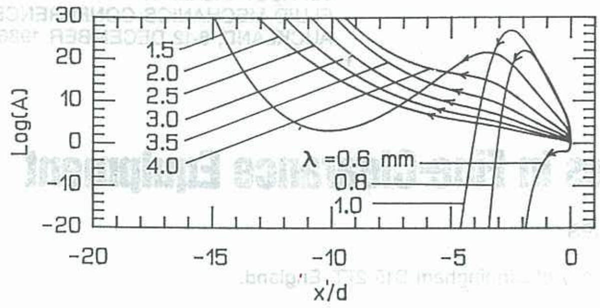

Figure 6 Traces of wave amplitude at upstream of the critical position ($x_i'/d=-0.01$)

illustration) and wavelength originating at a specified position, x_i', downstream of the critical position x*. Knowing the amplification or damping rate and the wave speed, it is possible to calculate the amplitude, A, and position of the disturbance of interest. Figures 5(a) and 5(b) give the variation of wave amplitude along the strip with different initial positions, x_i', downstream of x* and for different wavelengths. The short wave disturbances are seen to grow and decay rapidly in comparison to those of longer wavelengths (Figure 5(a)). In all cases, the location of the wave origination x_i' is very crucial in the determination of the final wave amplitude at solidification point at a long distance from the stripping zone as illustrated in Figure 5(b) which shows the variation of wave amplitude with distance along the strip for various wavelengths at different starting positions.

For the waves upstream of the critical point x*, similar calculations can be performed to trace the amplification or damping of a specified disturbance of a given wavelength and initial starting position. An illustration is given in Figure 6. Although it may be argued, as mentioned in the previous sections, that only the wave disturbances downstream of x* would affect the solidified film, the upstream disturbance amplitudes might be sufficiently large to cause wave breaks which could alter the mean flow conditions.

CONCLUSIONS

A solution for the stability of the surface waves of a thin film on a moving vertical surface under the influence of pressure gradient and surface shear stress is presented. The solution has been used to examine the instability of the coating film in a continuous hot dip galvanizing line controlled by air jets. Disturbances are found to propagate in the opposite directions from the critical stripping point and to decay at positions further downstream from the stripping zone under the effect of surface tension in certain line conditions.

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ACKNOWLEDGEMENTS

The author wishes to thank the management of BHP Steel International Group, Coated Products Division for permission to publish the information contained in this paper and especially his colleague, Dr W.Y.D. Yuen for his interest and suggestions in this study.