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Future Directions in Two-Phase Flow and Heat Transfer in Space

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ABSTRACT

Some areas of opportunity for future research in microgravity two-phase flow and heat transfer are pointed out. These satisfy the dual requirements of relevance to current and future needs, and scientific/engineering interest.

INTRODUCTION

Two-phase flow (or more broadly, multiphase flow) covers an extremely wide variety of fluid physics. To narrow the scope, only flows where one or more free interfaces exist, since these interfaces are generally sensitive to the presence or absence of gravity. These include liquid-gas, liquid-vacuum (or passive gas), and liquid-liquid combinations. Further, particular attention is paid to processes involved in space power systems, since power generation systems and chemical processing are the traditional preserves of two-phase flow and heat transfer. Also, studies of this nature focus on a particular need for space-based research. Finally, the underlying phenomena are poorly understood, even on the ground, and particularly so in space.

WHERE IS THE LIQUID?

A basic problem with partially-filled containers in space is the uncertainty as to just where the liquid is. As a result of the accelerations experienced during and after launch, globs of liquid may be floating about, coalescing with each other and with the wall layers. Furthermore, if g-jitter has significant energy in resonant, or subharmonic resonant, frequencies, large surface disturbances can be induced [1]. Finally, a well-wetting liquid (positive spreading coefficient), will simply creep out of an open container, or distribute itself over all exposed surfaces in a closed container. The reverse is true if wetting is very poor, as with mercury on stainless steel. This has serious implications for the reliability of thermocouples, conductivity probes and hot-film anemometers. It may be possible to control the motion of the contact line by heating or cooling the dry surface ahead of it [2,3], owing to thermocapillary (Marangoni) effects.

BOILING

Boiling is normally an efficient heat transfer process, but saturated pool boiling becomes unstable at moderate heat fluxes in space. Bubble departure from the heating surface is no longer assisted by buoyancy. As an example, n-pentane subcooled by 7 K gives a nucleate boiling flux of only 0.4 w/cm^2, but extrapolated towards saturated conditions, gives almost immediate film boiling (Fig. 10 of [4]. Subcooled pool boiling is more efficient, since the bubbles grow into the subcooled region and partially condense. Hence a steady heat flux can be sustained, provided that the subcooling can be maintained by external means. On the other hand, forced-convection boiling has minimum reliance on gravity to remove bubbles from the walls. Highly-subcooled forced-convection nucleate boiling is one of the most effective heat transfer processes known [5]. The critical heat flux in nucleate boiling, which represents local transition to film boiling, and hence is a key thermal design parameter, is poorly understood, even on earth.

CONDENSATION

Condensation runs into similar difficulties, in that gravity is no longer available to drain the condensate away. Furthermore, surface shear exerted by flowing vapor in the absence of gravity is not as effective, since the vapor velocity decreases as condensation proceeds. The ratio of the tube lengths for complete condensation of ammonia vapor has been calculated to be 1.5 for an 8 mm diameter tube in space vs. earth, and 30 for a 25 mm diameter tube [6]. It is, of course, always possible to add a non-condensible gas, such as air, to prevent complete condensation. However, it is well-known that even small quantities of air reduce the condensation heat transfer coefficients markedly. Capillary action, such as exerted by wicks and grooves in heat pipes, is used in space, but is limited in capacity, and can lead to low power-weight ratios in space radiators. An alternative, which does not seem to have been explored, is the use of rotating condensers, particularly for large space power applications.

GAS-LIQUID FLOWS

Cocurrent and countercurrent gas-liquid flows appear in many contexts on earth. Many flow regimes have been identified, depending on the orientation of the pipe and the flow directions of the two phases. However, in space countercurrent flow does not exist, and pipe orientation is immaterial. The situation is therefore much simpler, resolving down to three principal flow regimes: bubbly, slug and annular. Since the principal mechanisms for transport of heat and momentum are quite different for each flow regime, much more needs to be learned about the stability requirements for each regime, as well as for other regimes not yet identified.

BUBBLY FLOW

In a vertical pipe on earth, large bubbles rise more rapidly than small bubbles. Hence a large bubble acts as a "vacuum cleaner", coalescing with smaller bubbles above it, and eventually growing to be of the same order in diameter as the pipe. This does not happen at 0 g. The key distinction is that at 0 g the local relative velocity of gas and liquid, averaged over a local cell, is nearly zero, while at 1 g it is of the order of the rise velocity of a typical bubble in stagnant liquid. Hence, coalescence of neighboring bubbles is much less frequent in space, whereas breakup due to strong shear (large Reynolds numbers, pumps, expansions, etc.) continues as the mixture circulates through a closed loop. Hence one expects a nearly-uniform dispersion of fine bubbles after some time, with mean density and velocity which vary radially owing to wall shear effects. This is a considerable simplification, which may allow a simple treatment for pressure drop and void fraction calculations [7]. This is equivalent to the drift flux model [8], with the local relative velocity set equal to zero. For more detailed calculations, recourse must be had to the ensemble-averaged momentum and mass transport equations [9,10]. These have been quite successful, with suitable models for the drag, lift and turbulent Reynolds stresses, in fitting extensive experimental data taken on earth. These models, however, take as their velocity scale the local average relative velocity, which goes nearly to zero at 0 g. Furthermore, the wettability of the wall is a powerful influence in space, determining the nature of the wall layer. More work is therefore needed.

SLUG FLOW

As the gas content is increased, long gas slugs separated by liquid slugs appear. The liquid slugs are more stable in the absence of buoyancy effects, and hence of rise velocity of the gas into the liquid. In the central portion of the gas slugs there will be a nearly-stationary liquid wall film, again provided that the wall is well-wetted. If the wall is poorly wetted, as with mercury-nitrogen flow [11], asymmetric gas slugs hugging the wall appear. In microgravity these slugs may be stationary. Hence, with either good and poor wetting, boiling can result in burnout even before the annular flow regime is reached. The stability to rupture of the wall film and its wetting tendency are thus important in determining the critical heat flux (CHF).

ANNULAR FLOW

In isothermal laminar gas-liquid flow with well-wetted walls, the wall film is unstable by a linear analysis [12,13]. This is probably also true for turbulent-turbulent flow. Because the restoring force is weak, droplets detach from the free interface and redeposit on the wall film. If, in addition, the wall film is evaporating, it eventually becomes unstable and ruptures. It can break down into rivulets, which can still provide effective cooling [14,15]. Further theoretical and experimental study of the necessary conditions is needed. With turbulent shear, as with nitrogen-Freon cocurrent flow [16], a transient dryout-rewetting zone may be expected prior to the development of rivulets. Wall wettability is again important.

THIN LIQUID FILMS

As noted above, these appear naturally on well-wetted walls in slug and annular flow. These films give excellent heat and mass transfer, but their rupture and dryout can lead to equipment overheating. Very thin films separate bubbles formed in forced-convection subcooled nucleate boiling from the wall. This causes the bubbles, growing and collapsing while attached to the heated wall, to act as miniature heat pipes. This is responsible, at least in part, for the very high heat fluxes observed on earth, as in cooling the throat section of rocket motors [17]. These films also appear in many other contexts, such as in manufacturing processes and biological functions. Because of their thinness, they are amenable to detailed computation and experimental analysis, with minimum reliance on empirical modeling [18]. Fig. 1 shows the computed unsteady film profile, based on a nonlinear evolution equation, for a thin heated film on a horizontal surface, taking into account van der Waals, surface tension, vapor recoil and mass loss effects [14]. The initial sinusoidal perturbation slowly deforms, but downwards fingering becomes important when the vapor recoil and van der Waals effects become important. The calculation seems to indicate film rupture, but surface wetting has not been taken into account. The final stages of rupture, consisting of the formation and spreading of a dry spot, have not yet been analyzed.

Fig. 2 shows a three-dimensional calculation for a falling film, with initially a two-dimensional surface wave in the direction of flow down a heated wall. Marangoni effects enhance the transfer of energy from the streamwise wave to a cross-stream wave. This eventually results in longitudinal rolls, which further deepen into pre-rivulets [19].

ELECTROSTATIC LIQUID FILM RADIATOR

Electrohydrodynamic forces, which are generally weak compared to gravity on earth, can be significant in space. In keeping with the general theme of basic studies related to space power systems, a novel lightweight space radiator concept is discussed here. This is based on the fact that an electric field, regardless of its sign, always pulls a conductive liquid into a non-conductive region. This effect can be used to stop a leak of a thin liquid-metal film through a puncture of the radiator wall caused by micrometeorite impact [20-23]. A very thin membrane is used for the body of a closed hollow radiator with internal localized electric fields, switched on as necessary when a leak is detected. Such leaks will be quite infrequent, since nearly all micrometeorites are smaller than a few microns in diameter. Punctures of this size will be sealed by capillary effects, since the internal pressure is the vapor pressure of the liquid metal film flowing along the wall of the radiator (0.3 dynes/cm^2 for lithium at 700 K). This is not possible with heat pipes, which have a substantial internal pressure. There is thus a potential weight advantage of about 2 or 3 to one for this type of radiator compared to heat-pipe radiators. The electrostatic radiator may consist of stationary cylinders or rotating disks, with view factors greater than 0.8. Fig. 3 shows a stability calculation for a lithium liquid film, immediately after switching on the electrostatic film after detection of a surface leak. It is seen that a surface wave is immediately induced, but this has a maximum amplitude of about 0.15 mm, and then gets washed downstream. Hence there is no danger of shorting out the electrode, which is situated 1-2 cm. away from the film. The pressure depression is sufficient to stop the leak with a safety factor of about two. However, the stability of the entrance walljet and collection of the exiting liquid film in space need further study.

COMPUTATION

Advanced codes for efficient representation of large surface deformations on short time scales with heat and mass transfer are needed. In view of the enormous costs of experimentation in space, computations on earth have the potential for considerable cost savings. Work along these lines have been progressing in a number of locations. The Los Alamos code, RIPPLE [24], as an example, models surface as a volume force derived from a continuum surface force model. Free surface elements are represented by volume-of-fluid data. Another promising code is a general multidimensional hyperbolic equation solver [25,26], which uses a cubic polynomial interpolation scheme, with the gradient of the quantity as a free parameter, in a stable explicit scheme. This has produced good resolution for shock wave interaction with a liquid drop, and for laser-induced evaporation dynamics.

THERMOCAPILLARY EFFECTS

A number of papers in this conference deal with thermocapillary effects. These can dominate in the absence of gravity. As the Marangoni number, as well as other parameters, is increased, thermocapillary flows can become 3-D, time-dependent and eventually chaotic. G-jitter effects can additionally be superimposed. An evaporating drop can build up a surface temperature gradient until a critical Marangoni number is reached, leading to internal mixing. On the other hand, thermocapillary convection in fluid layers may be stabilized by nonplanar flow oscillations or possibly by laser pulsing. Similarly, removal of entrapped bubbles from melts can be induced by imposing a mean temperature gradient on the liquid. The bubbles tend to "swim" towards the higher temperature.

CONCLUSIONS

A number of areas of opportunity for research related to two-phase flow and heat transfer in the presence of free interfaces have been pointed out. Ground-based analysis, experimentation and computation should be emphasized, in view of the high cost of space experiments. New phenomena result in the absence of gravity, and old ones can become much less important. There is considerable room for imaginative work.

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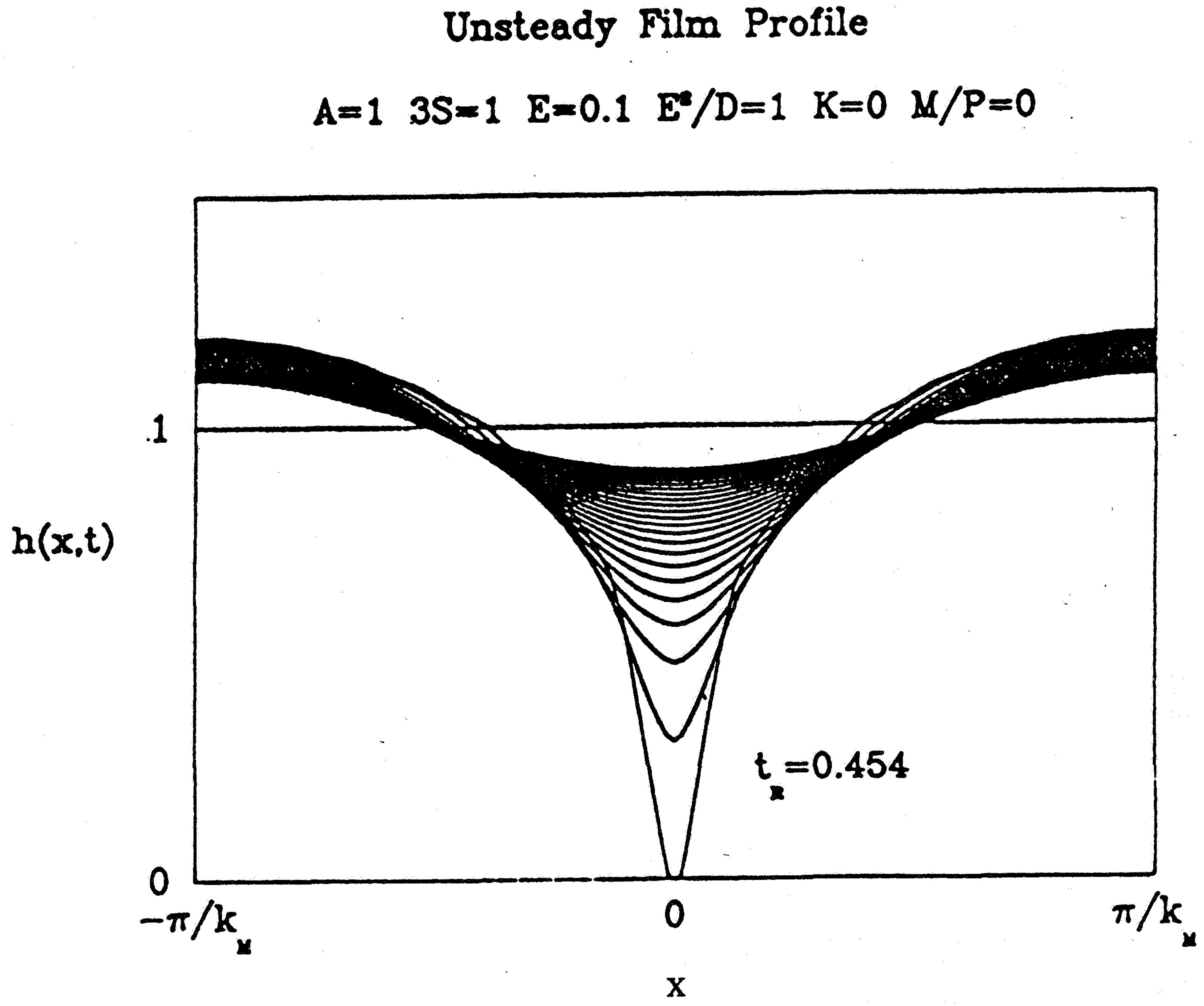

Fig. 1 Development of a Fingering-Type Instability in a Horizontal Evaporating Liquid Film with Surface Tension, Vapor Recoil, Mass Loss and van der Waals Effects

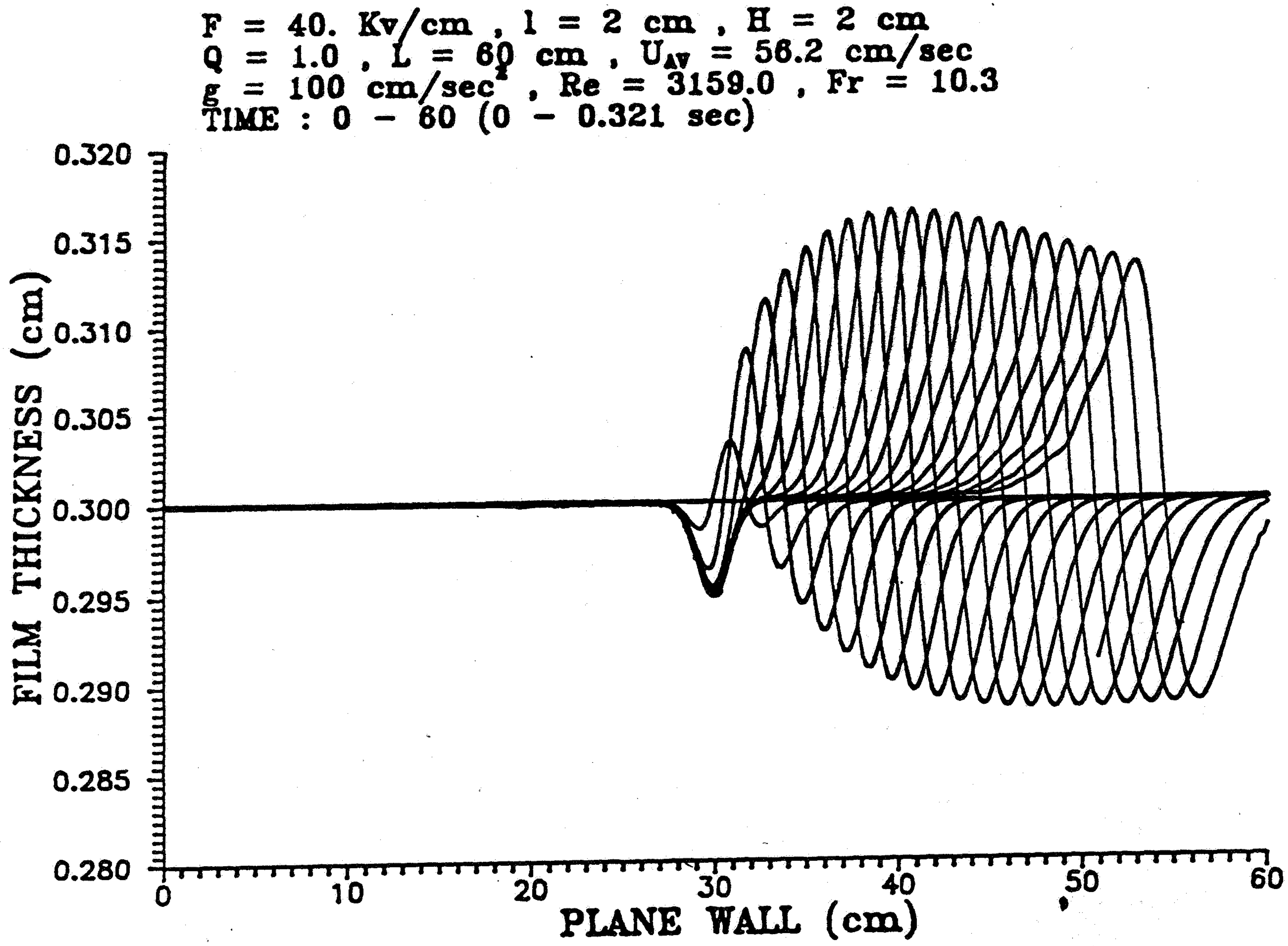

Fig. 2 Surface Wave in a Liquid Lithium Film Falling Down a Plane Wall after Switching on Electrostatic Field

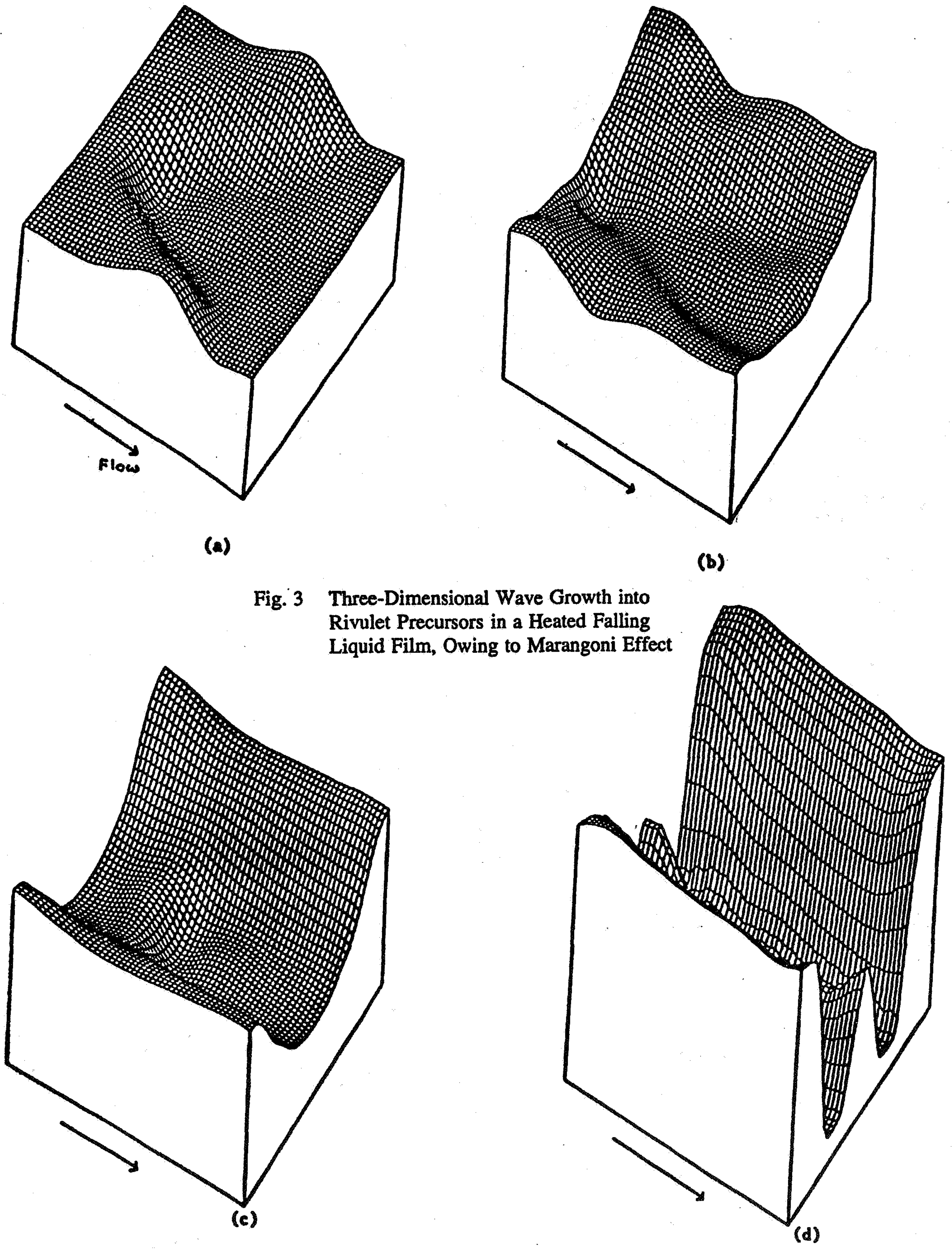

Fig. 3 Three-Dimensional Wave Growth into Rivulet Precursors in a Heated Falling Liquid Film, Owing to Marangoni Effect