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THINNING AND RUPTURE OF A THIN LIQUID FILM ON A HEATED SURFACE

Progress Report
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1. INTRODUCTION

1.1 Objective

The objective of this work continues to be the study of the dynamics, stability and rupture of thin liquid films, especially with heat and/or mass transfer. These films appear in many engineering processes, such as film coating, gas absorption, condensation, and especially cooling of hot surfaces. Surface waves may be detrimental, leading to film breakdown, with consequent equipment overheating, or beneficial, as when mass transfer coefficients are increased.

1.2 Stratified Flows

In the past year the analysis has been extended to stratified flow of two thin incompressible, immiscible layers between stationary parallel walls, subject to body forces and surface tension. The linear stability analysis results in two eighth-order Orr-Sommerfeld equations, which are combined into a single sixteenth-order equation with periodic boundary conditions. For the flow-specified problem there are seven dimensionless parameters: Reynolds number, gravity number, density ratio, viscosity ratio, base-state layer thickness (or volumetric fraction), surface tension number, and angle of inclination. A long-wave generalized evolution equation of the Benney type is derived, which reduces for special cases to previously derived results. Upon linearization, a lubrication pressure is derived, which is the result of three different inertial effects on the perturbed flow. It couples the density stratification and viscosity stratification effects, each of which can be individually stabilizing or

destabilizing, through the volumetric flow constraints. For the horizontal case, regions exist where lubrication pressure exerts a stabilizing influence for certain density ratios. For the inclined channel, four different stability diagrams are found in wavenumber/flow rate space, representing the competition of different physical effects.

A small-amplitude analysis in the neighborhood of the linear neutral stability boundary to obtain a Kuramoto-Sivashinsky (KS) equation is performed. For small "group" velocity, (which may be pertinent to the flooding phenomenon in countercurrent parallel flows), a different scaling yields an extended KS equation, containing both quadratic and cubic nonlinearities. This cubic KS equation, or 3KS equation, possesses some new reflection, symmetry, and replication properties. The bifurcation diagrams are traced out to determine the effect of the cubic term. It is found that the symmetry-breaking bifurcation of the KS equation is now imperfect. Modulated travelling waves of large amplitude may bifurcate from the traveling wave solutions, and hysteresis loops may be formed, which are suggestive of flooding.

1.3 Falling Film Experiment

The experimental program is designed to confirm the range of validity of the theoretical analysis, and to determine its practical limits. Surprisingly, the original Yih-Benjamin linear stability theory for a single liquid layer draining down an inclined or vertical wall has never been fully confirmed. This is because of the sensitivity of the system to small random perturbations, particularly in the flow entrance region. Chaotic waves rapidly appear unless a single-frequency forcing function is imposed at the liquid inlet. Thus, the appearance of two-dimensional ring waves, owing to amplification of the fastest-growing wave number, has not been seen experimentally in the unforced system. However, by careful balancing, and

operation under conditions of extreme quiet, the Yih-Benjamin predictions of wave number, velocity, frequency and linear amplification rates were fully confirmed for Reynolds numbers less than ten. To supplement the resistivity probe system, described previously, a fluorescent dye was introduced into the glycerin-water mixture, so that the waves can be visualized by ultraviolet illumination. A mirror system has been installed so that a complete 360° view of the tube is obtained in a single frame. This allows the measurement, using a CCD camera and image digitization, of the development of circumferential secondary waves from the primary ring waves. This development is rapid when the tube is heated, owing to thermocapillary effects, as predicted by Davis and Joo (1992a). Eventually, chaotic waves develop.

1.4 Spatially Developing Nonlinear Waves

The stability analyses are generally predicated on periodic boundary conditions, whereas in actual practice the liquid is introduced at the liquid inlet point. This can result in initial transients and in spatially-growing or -decaying waves. A numerical investigation is under way to examine this behavior for nonlinear waves on a falling film.

2.0 PERSONNEL

A. Knaani received the Ph.D. in Mechanical Engineering during the report period.

3.0 PUBLICATIONS

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S. H. Davis and T. Erneux, "Nonlinear rupture of free films", Phys. Fluids A (to appear 1993).

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4.0 PRESENTATIONS

S. G. Bankoff

"Stability of Thin Heated Liquid Films", International Heat Transfer Assembly, Rome, Italy, Sept. 21, 1992.

"2-D and 3-D Instabilities of Thin Liquid Films Falling on Heated Inclined Plates", 4th Japan-U. S. Seminar on Two-Phase Flow Dynamics, Berkeley, CA, July 5-11, 1992 (with S. W. Joo and S. H. Davis).

"Significant Questions in Thin Liquid Film Heat Transfer", Symposium on Significant Questions in Heat Transfer: The Fundamental Issues in Small-Scale Heat Transfer, Winter Annual Mtg., ASME, Anaheim, CA, November 9, 1992.

"Stability and Dynamics of Thin Heated Liquid Films", Mechanical Engineering Department, Technion, Haifa, Israel, Dec. 21, 1992.

"Two- and Three-Dimensional Instabilities of Falling Liquid Films", Dept. of Fluid Mechanics and Heat Transfer, Tel-Aviv University, Tel Aviv, Israel, Dec. 23, 1992.

"Stability of Thin Films", Chemical Engineering Department, University of California, Santa Barbara, CA, February 2, 1993.

"Stability of Thin Films", Mechanical, Aerospace and Nuclear Engineering Department, University of California, Los Angeles, CA, February 4, 1993.

Keynote Lecture, "Stability and Dynamics of Thin Heated Liquid Films", 6th International Symposium on Transport Phenomena in Thermal Engineering, Seoul, Korea, May 9-13, 1993.

S. H. Davis

"A Mechanism for Rivulet Formation in Heated Falling Films", Laboratoire d'Acoustique, École Centrale de Lyon, (1992).

"Hydrodynamics and Heat Transfer of Thin Liquid Films", National Renewable Energy Laboratory, Golden, Colorado, (1992).

"Coupled Instabilities in Heated Falling Films", Department of Applied Mechanics and Engineering Science, University of California, San Diego, CA, (1992).

"Coupled Instabilities in Thin Liquid Films", Department of Applied Mathematics and Theoretical Physics, University of Cambridge (1992).

"Contact-Line Dynamics", National Institutes of Standards and Technology, Gaithersburg, MD (1993).

B. S. Tilley

"Stability of Stratified Flows in an Inclined Channel", 44th Annual Mtg., Fluid Dynamics Div., American Physical Society, Tallahassee, FL, November 22, 1992, (with S. G. Bankoff and S. H. Davis).

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