TRANSIENT FLOW AND HEAT TRANSFER PHENOMENA IN INCLINED WAVY FILMS

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INTRODUCTION

Film flow occurs in a variety of process equipment, including condensers, falling film evaporators, absorption columns and two-phase flow reactors. In a range of Reynolds numbers of interest to such engineering applications ($1<Re<400$) the flat free surface is unstable and traveling waves develop. These surface waves have long been known to affect heat and mass transfer across the film[1]. However, the flow problem is extremely complex because the location of the free surface varies continuously and must be found as part of the solution. Consequently, efforts to explain the influence of waves on transport processes have been mostly heuristic[2-5] and only few studies have adopted rigorous numerical solution of the flow and energy transport equations[7-10].

Of particular interest among the various wave forms adopted by the free surface are solitary waves, ie. strongly nonlinear humps proceeded by capillary ripples, which attain a stationary shape and are separated by relatively long stretches of flat substrate. It has been observed[6] that in many circumstances the downstream evolution of film flow tends to a series of solitary waves. This occurs directly when regular disturbances of low frequency are introduced at the inlet, and indirectly (through a sequence of nonlinear interactions) when the inlet disturbance consists of random noise.

Thus, the goal of the present contribution is to investigate computationally the dynamics of an unstable inclined free surface as well as its influence on heat transfer across the film. The full Navier-Stokes equation is solved by a finite-element method, delineating the evolution of the free surface and the flow field below the waves[7]. The energy equation is solved subsequently with the same method, providing information on the effect of waves on heat transfer. The flow is considered from the initial stages of linear instability up to the development of stationary traveling waves. Particular emphasis is placed on the role of solitary waves. The present study is closely related to recent work by Miyara[10], who used a finite-difference method to investigate heat transfer on a vertical film.

MATHEMATICAL FORMULATION

Two-dimensional, gravity-driven flow along a constant-temperature plane with inclination φ is considered. A full description of the problem is provided by the continuity, Navier-Stokes and energy equations. Boundary conditions for the flow problem are no-slip and no-penetration along the wall $y=0$, and the kinematic condition and a balance of forces along the unknown free surface $y=h(x,t)$. An additional boundary condition at the inlet

$$h(0,t)=H+A\cos 2\pi ft \qquad A<<H$$

introduces small periodic disturbances of frequency f, and an appropriate boundary condition is applied at the outlet to minimize upstream distortions. In the energy problem, the liquid enters with a uniform temperature T_0, the wall is set at a constant temperature T_1 and the air above the free surface is considered to provide a constant heat transfer coefficient. The complete flow and heat transfer problem is described by the Reynolds, *Re*, the Weber, *We*, and the Peclet, *Pe*, dimensionless numbers.

The unknowns are the velocities u and v, the pressure p, the temperature T and the location of the free surface. These are expanded in terms of Galerkin basis functions as follows:

$$u = \sum_{i=1}^{9} u_i \varphi^i, \quad v = \sum_{i=1}^{9} v_i \varphi^i, \quad p = \sum_{i=1}^{4} p_i \psi^i, \quad T = \sum_{i=1}^{9} T_i \varphi^i, \quad h = \sum_{i=1}^{3} h_i \varphi^i$$

where φ^i are biquadratic and ψ^i bilinear basis functions. The governing equations and the kinematic boundary condition are weighted integrally with the basis functions and are evaluated numerically using nine-point Gaussian quadrature. Time integration is performed by a Crank-Nicolson scheme and the resulting system of nonlinear algebraic equations is solved with the Newton-Raphson method.

RESULTS AND DISCUSSION

The entire evolution process of inlet disturbances is followed computationally. Initial results of wave celerity and exponential growth rate are in agreement with the predictions of spatial linear stability analysis. The fully-developed wave profiles are also accurately captured, as demonstrated by comparisons with relevant data. The effect of disturbance frequency on the stationary form of the free surface is shown in Figure 1a-d.

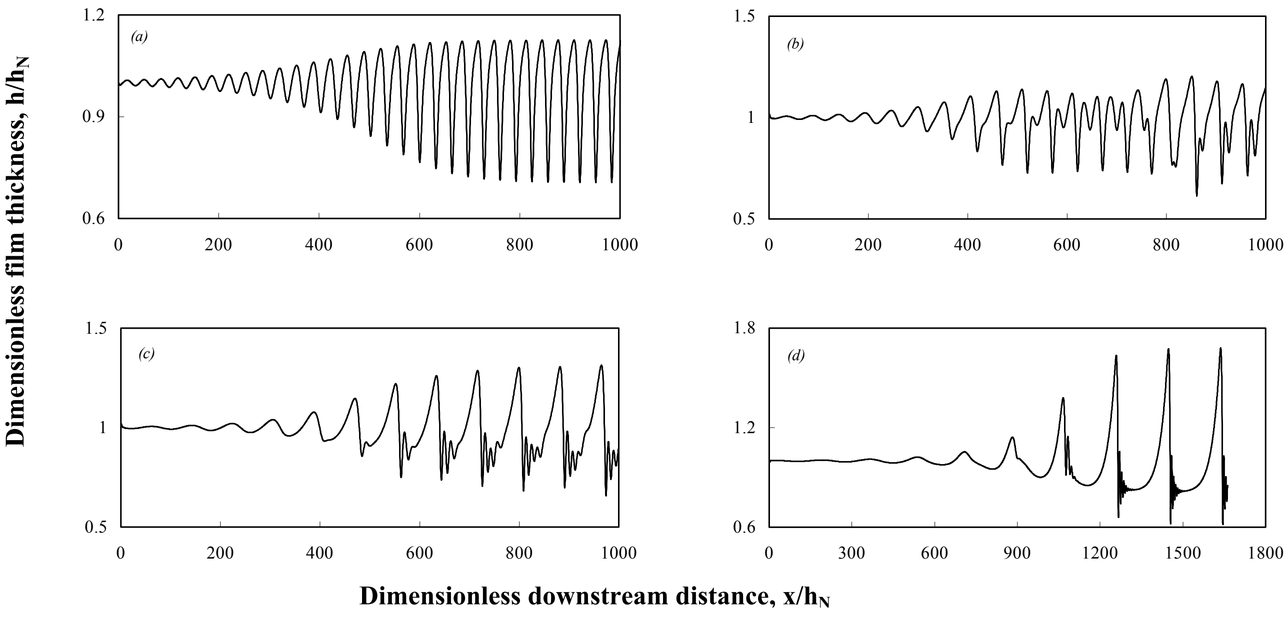

Figure 1: Spatial evolution of the free surface for a film with Re=19.33, We=5.43 and inclination φ=6.4°. The periodic inlet disturbances have frequency (a) 7 Hz, (b) 4.5 Hz, (c) 3 Hz and (d) 1.5 Hz.

All stages of downstream evolution are documented in detail. Frequency spectra of the temporal variation of the free surface at different locations along the wall indicate the transition from a monochromatic disturbance to the broadband Fourier structure of nonlinear waves. Indicative profiles of the evolution towards a solitary hump are demonstrated in Figure 2.

The velocity field of solitary waves is found to exhibit a strong deviation from the parabolic shape in front of the main hump. A transient region of flow reversal is formed and travels with the wave celerity.

This is shown to affect heat transfer from the wall in a fundamentally different way than the flow field produced by a series of closely-spaced periodic waves.

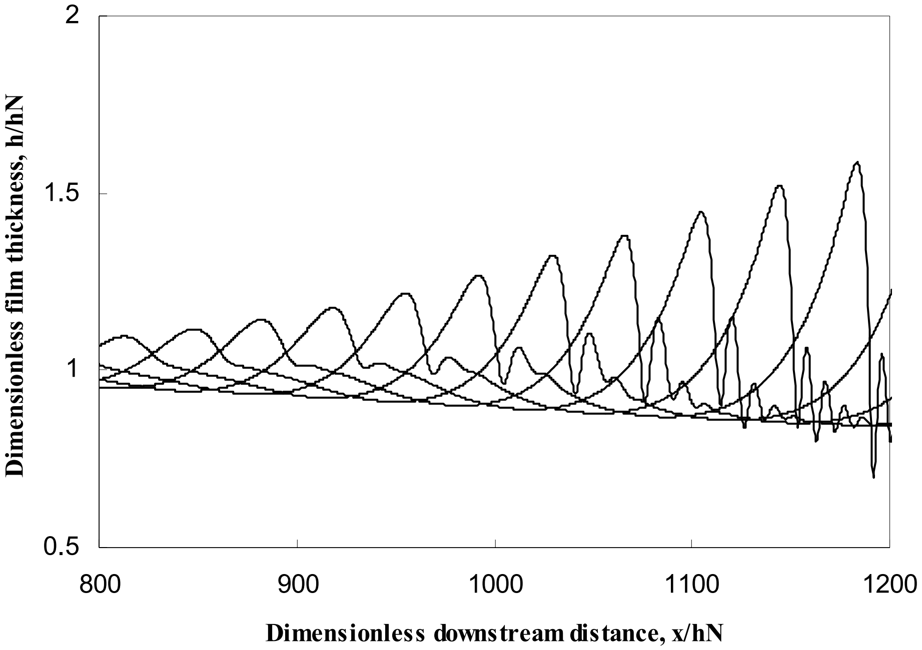

Figure 2: The nonlinear evolution towards a solitary wave in a flow with Re=19.33, We=5.43 and inclination φ=6.4° and inlet disturbances of frequency 1.5 Hz.

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