

Flow Instability of Glycerol/Water/Triton-X-100 Thin Liquid Film System

Gang-Chi Chen and Y. C. Chiew, Department of Chemical & Biochemical Engineering, Rutgers University, Piscataway, NJ
J. E. Valentini, Sterling Diagnostic Imaging, Brevard, NC

Abstract

The flow stability of Glycerol/water/Triton-X-100 nonionic surfactant of single layer liquid film flowing down an inclined plane was systematically studied in this work. Capillary wave at the liquid surface was measured by capillary wave/laser detection method. Specifically, we examined the effect of Triton-X-100 surfactant on the damping of capillary waves on the free surface of glycerol/water liquid film. The stability of capillary wave disturbances on the liquid surface was characterized by measuring the wave damping coefficient β. The stability and instability boundary is identified by the condition $\beta = 0$. The corresponding value of the wave number at the $\beta = 0$ condition is referred to as the critical wave number, $\alpha_c = 2\pi h/\lambda$, where h is the film thickness. This critical parameter, α_c, is used to characterize the flow's stability, and determined as a function of Reynolds Number, Elasticity Number and Weber Number. We found that the flow stability increases with the surfactant concentration. At high concentrated solutions (above the CMC), it was found that, for a fixed Reynolds Number, α_c is independent of surfactant concentration and the Weber Number. A comparison of the effects of surfactant elasticity and surface tension to flow stability is discussed.

Introduction

Studies of thin liquid films on an inclined plane have always been an attractive subject to most of the coating industries. High speed coating is a process which involves depositing a thin uniform layer and/or layers of liquids on top of a solid substrate. It is an extremely important core technology in the manufacturing and production of high quality photographic and x-rays films. Slide coating is one of the coating techniques that is employed in the coating of photographic films. In this technique, liquids are injected at controlled conditions through one or more slots of an applicator die onto the inclined surface of the die. The injected liquid flows laminarly as a film down that inclined face onto a smooth solid substrate. In order to obtain high quality coating films, fluid mechanical stability of the liquid film/films flowing down the inclined of the applicator must be maintained. The window of flow stability of these liquid films is crucially influenced by the operating conditions (e.g., flow rates, vacuum) and the bulk and surface properties of the fluids.

Numerous work had been done in the past in both theoretical (or simulation) and experimental area to characterize the flow's stability nature. Yih[1] and Benjamin[2] first used the analytical treatments of Orr-Sommerfeld equation to explore the instability nature of Newtonian fluids for low Reynolds number. They predicted that vertical film flow is always unstable. Higher Reynolds number's flow are examined with numerical technique and experimental data by Whitaker[3,4]. Krantz and Goren[5] performed a classical stability analysis of the Orr-Sommerfeld equation with fourth-order polynomial. The authors also calculated the wave amplitude data of thin oil layer flow on the slide surface as a function of distance. The conditions of flow stability along a harmonically oscillating liquid surface has been analyzed by Shabunina et al.[6] with the linear approximation methodology. Weinstein et al.[7] examined the propagation of surface waves for a single layer film flowing down an inclined plane, where the plane is oscillating in the flow direction.

The addition of surfactant is also commonly used by investigators to characterize the flow nature of the single layered thin liquid film. A series of flow stability studies of a thin liquid film with surface active agents have been reported in the literature by Whitaker et al.[3,8,9,10] and others[11,12]. Flow visualization techniques are used to observed the surface velocity of the flow by Whitaker et al. The derivation of the surface velocity profile of the studied system was used to analyze the flow stability dependence on the adsorption kinetics and the equilibrium relation, and the compositional surface elasticity. Baumlin[12] did the measurement of the damping with the addition of soluble surfactants in the flow-down-slide system with a laser deflection method which is very similar to the technique used in our research lab. In general, it is well accepted that surface active agents and surfactants are effective stabilizers for liquid films by surpressing or retarding the onset of waves at the free surface. In the current experimental investigation, our emphasis is to examine and characterize the effects of flow rates, bulk viscosity, and the addition of Triton-X-100 surfactant on the damping of capillary waves on the surface of a single layer liquid film, and the role of surface tension and surface elasticity in stabilizing the thin liquid film on an inclined plane. The main purpose of this study is to quantify the surface wave damping and establish the relationship between the surface properties and the flow stability on the inclined surface.

Experimental Procedure and Materials

The experimental apparatus used in the current studies include the following four individual units: (i) a device that generates propagating capillary waves (of frequencies ranging from 10 Hz to 500 Hz) on the surface of a liquid film flowing down an incline; (ii) an optical detection system with a laser source; (iii) a slide coater (flow-down-slide) unit; (iv) a pump which recirculates the liquid into and out of the slide coater unit.

Surface capillary waves were generated by applying an AC with a DC offset voltage between a sharp blade and the liquid film. The amplitude of the excited surface wave is detected by the specular reflection of a laser beam from the free surface of the liquid film flowing down the slide to a position sensitive diode. The amplitudes of the propagating capillary wave are measured through lock-in technique. Details of the detection principle and a schematic of the optical detection system can be found in earlier publications.[13,14] In current studies, capillary waves are generated by applying an AC (100 ~ 500 millivolts) voltage and a DC off-set voltage (100 ~ 500 millivolts) between the sharp metal blade and the liquid surface. The surface wave is scanned over a distance of 0.25 cm with a He-Ne laser by a computer-controlled linear translation motor, and wave amplitude are recorded as a function of distance from the wave generator through lock-in technique.

The lab-scaled flow-down-slide unit is made of stainless steel and consists of several individual parts. These separate parts are assembled together by tightly fastened screws and rubber sealant for leak prevention. The incline of the unit is 37° relative to the horizontal. The path of the premetered flow on this inclined plane surface is guided by a pair of glass slides which cover an area of 12.5 cm in length and 7 cm in width. The unit has three evenly spaced inlet channels located underneath the slide surface. The channels allow the simultaneous introduction of a maximum of three liquid streams forming a multilayer stratified film flowing down the incline of the slide.

A Posi-Flo II Peristaltic Pump purchased from Gelman Sciences Inc. is used to recirculate the liquid into and out of the slide coater. This equipment is capable of delivering liquid from 0 to 1600 ml/min by changing the dial-settings. For a single layer solution experiment, the liquid can be collected from the outlet of the flow-down-slide unit and recirculated back to the inlet of the unit. A 1-liter bottle with inlet and outlet channels is installed between the pump and the inlet of the flow-down-slide unit to reduce the pulsating disturbance on the flow due to the pump.

The entire experiments were carried out at flow rates in the range of 200-500 ml/min which will provide realistic simulation of coating process in the pilot plant production. Based on our flow rate calibration (not shown), we find that a dial-setting ranging from 1.5 to 3 satisfies the flow rate requirement. Based on these considerations, we have selected the range of dial-settings between 1.6 and 3.0 for most of our experiments. A calibration curve (not shown) for these chosen dial-setting ranges yield flow rates between 2.0 and 7.2 ml/sec.

Current studies investigate the flow stability of Glycerol/water solution with Triton-X-100 nonionic surfactant as additive. Glycerol of spectrophometric grade and Triton-X-100 of electrophoresis grade were purchased from Aldrich Chemical Company, Inc. and Fisher Scientific, respectively. They were used as received without further purification.

Effect of Triton-X-100 Surfactant on Damping of Surface Waves

It is well known that surface active agents and surfactants are effective stabilizers for liquid films by surpressing the onset of waves at the free surface. In the present studies, we examine the effect of Triton-X-100 surfactant on the damping of capillary waves on the free surface of 40:60 (by volume) glycerol/water solutions on the down-the-slide unit. The viscosity of 40:60 (by volume) glycerol/water solution is 4.0 cp. In these experiments glycerol/water solutions with a fixed concentration of Triton-X-100 surfactant are used. Capillary waves at known frequencies were generated and the damping coefficient β were measured as a function of bulk viscosity and surfactant concentrations.

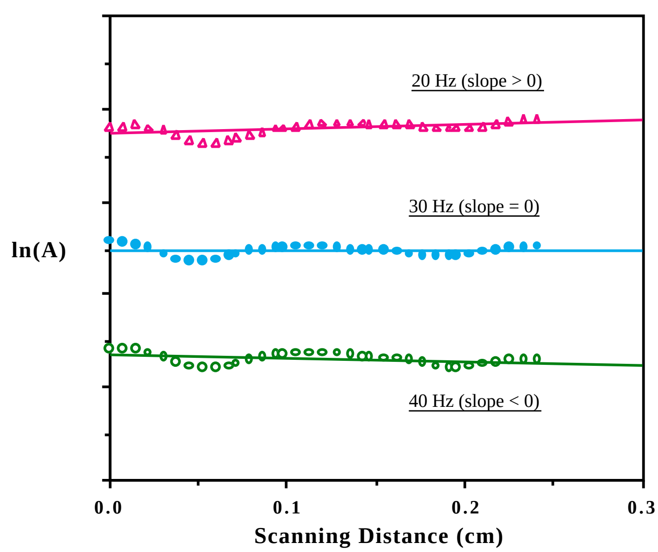

Figure 1. Damping coefficients of 40-60/Glycerol-water system with 2.01×10^{-3} wt% Triton-X-100.

Figure 1 shows a plot of measured wave amplitude versus distance on the slide at different perturbation frequencies ranging from 20 to 40 Hz for a 2.01 $\times$ 10^{-3} wt% Triton-X-100/glycerol/water system. The damping coefficient β of the excited wave is given by the slope of the logarithm of the measured amplitude with distance. At a frequency of 40 Hz, the wave is stable and the amplitude decays with distance giving a positive damping coefficient. However, at a lower frequency of 20 Hz, the wave amplitude increases with distance indicating instability; the damping coefficient β is negative.

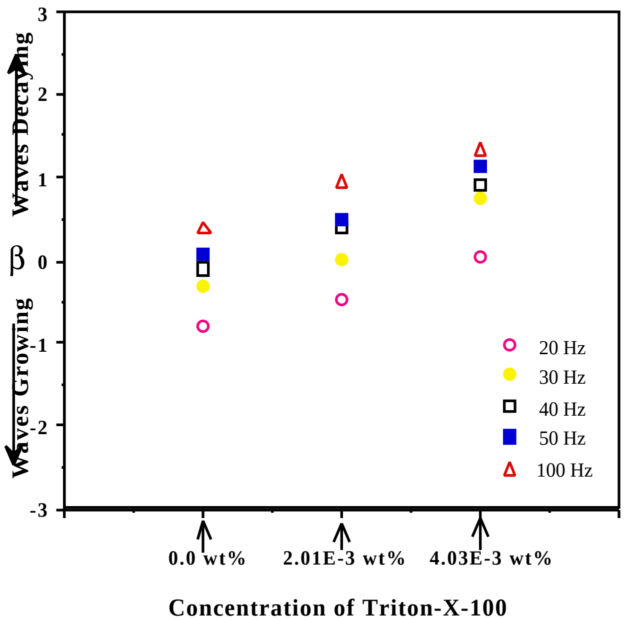

Figure 2. Damping coefficients at various frequencies versus Triton-X-100 concentration of 40-60/Glycerol-water system. (Reynolds #=20.7)

Figure 2 illustrates the effects of perturbation frequencies and surfactant concentrations on the damping of surface wave for Reynolds number Re=20.7. Note that at a fixed surfactant concentration, the damping coefficient β decreases with decreasing frequency. As the wave frequency decreases, β changes from a positive value (decayed, stable) to a negative (growing, unstable) one indicating that the flow becomes unstable to low frequency disturbances. The effect of the addition of surfactants on the flow stability is also observed. The damping coefficient β is found to increase with surfactant concentration indicating that surfactant tends to suppress the growth of surface waves.

In addition to measured values of damping coefficient β, it is also convenient to use the dimensionless wave number $\alpha \equiv 2\pi h / \lambda$ to characterize the surface wave; here, h represents the thickness of the liquid film and λ represents the wavelength. At a fixed Reynolds number, there exists a critical frequency f_c at which the flow be-comes unstable, i.e., waves with frequency $f < f_c$ become unstable, while waves with $f > f_c$ are damped out. For a given Reynolds number, the damping coefficient data are fitted to a polynomial. This stability-instability boundary or the critical frequency f_c is given by the condition β=0 and is obtained by interpolation. With the critical frequency f_c calculated, the critical wavelength λ_C, that is, the wave-length of the wave with frequency f_c (this is the wave with a damping coefficient β=0 for a given solution at the specified Reynolds number) can be obtained by reading off the value of λ at the critical frequency. Figure 3 shows the critical wave number $\alpha_C \equiv 2\pi h / \lambda_C$ plotted as a function of Reynolds number for glycerol/water solutions at three different Triton-X-100 concentrations. At a fixed concentration, the region that lies above each curve represents the stable zone. Conversely, the region that lies below the curve represents the unstable zone. These data are extremely useful since they provide valuable information on the relation between flow stability, Reynolds number (flow rate, viscosity of solution, and thickness of film) and surfactant concentrations.

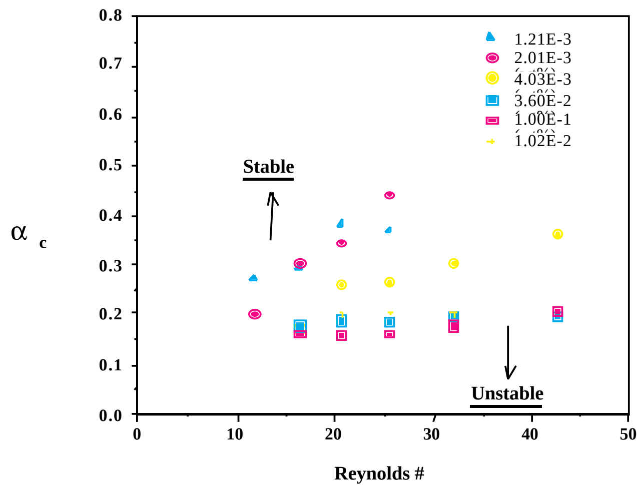

Figure 3. Measured critical wave number at various Triton-X-100 concentration versus calculated Reynolds number of 40-60/Glycerol-water system.

Figure 4 shows the dependence of calculated local surface elasticity and surface tension (7.5 cm downstream from entrance) as a function of Triton-X-100 bulk concentration at Re=20.7. It indicates that when the bulk concentration is greater than 1.0 $\times$ 10^{-2} wt%, local concentration of Triton-X-100 (7.5 cm downstream from entrance) at the liquid surface is greater than 3.5 $\times$ 10^{-2} wt%; hence, the surface tension remains constant. Figure 5 shows the measured critical wave number, α_c, plotted as a function of Triton-X-100's bulk concentration for several Reynolds numbers' groups (Re = 20.7, 25.5, and 32.0). As mentioned earlier, α_c vs. concentration plot represents the stable-unstable boundary of the flow. It is seen that the α_c initially decreases with surfactant concentration and then reaches to a constant at higher concentrations. These results indicate that the surface tension plays an important role in stabilizing the flow.

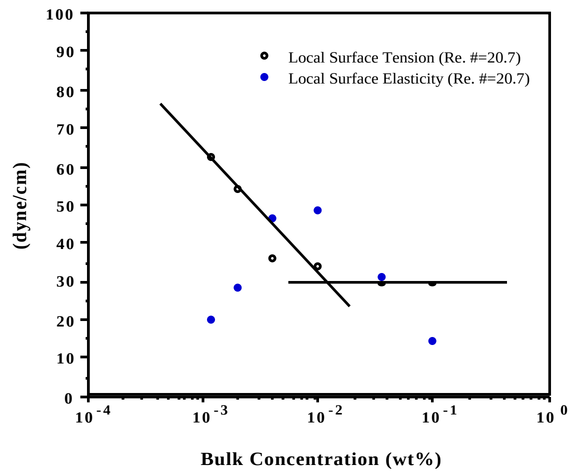

Figure 4. Measured local surface tension and modulus as a function of Triton-X-100 concentration of 40-60/Glycerol-water system.

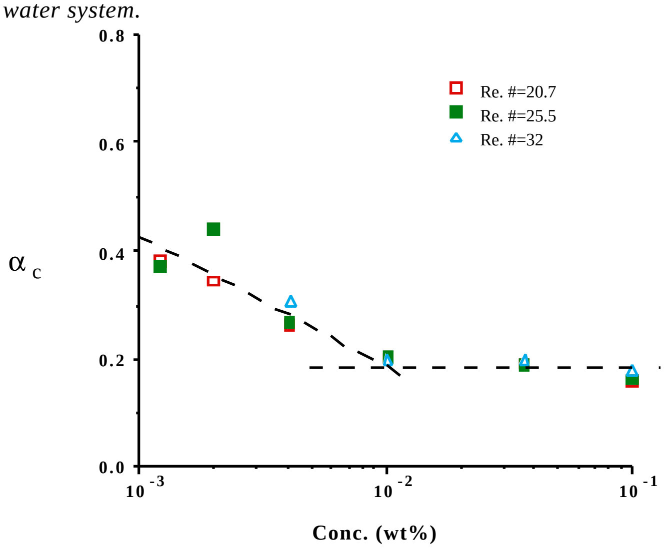

Figure 5. Critical wave number as a function of Triton-X-100 concentration of 40-60/Glycerol-water system.

Conclusions

In the current study, the stability of Glycerol/water solution (with/without Triton-X-100 nonionic surfactant) of flow down an inclined plane. We quantify the surface wave damping and establish the relationship between the surface properties and the flow stability on the inclined surface. Wave motion of the flow on the solution's surface has been identified by the capillary wave/laser detection method. We examined the effect of Triton-X-100 surfactant on the damping of capillary waves on the free surface of glycerol/water coatings on an inclined plane with the damping coefficient β. The values of β are found to be a very strong function of solution's viscosity. The critical wave number, $\alpha_C \equiv 2\pi h / \lambda_C$, is used to characterize the flow's stability, and determined as a function of Reynolds Number, Elasticity Number and Weber Number. A plot of stability/ instability boundary of the flow was obtained as a function of Reynolds numbers for the current studied system. It has been found that stability of the flow increases with the surfactant concentration. At high concentrated solutions (ranging from 1.02×10^{-2} wt% from 0.1 wt%), it was found that, for a fixed Reynolds Number, α_c is independent of surfactant concentration and the Weber Number. The data reveals that there is a strong correlation between surface tension and flow stability indicating that surface tension plays an important role in flow stabilization.

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