FUNDAMENTAL PROCESSES OF ATOMIZATION IN FLUID-FLUID FLOWS

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ABSTRACT

This paper discusses our proposed experimental and theoretical study of atomization in gas-liquid and liquid-liquid flows. While atomization is a very important process in these flows, the fundamental mechanism is not understood and there is no predictive theory. Previous photographic studies in (turbulent) gas-liquid flows have shown that liquid is atomized when it is removed by the gas flow from the crest of large solitary or roll waves. Our preliminary studies in liquid-liquid laminar flows exhibit the same mechanism. The two-liquid system is easier to study than gas-liquid systems because the time scales are much slower, the length scales much larger, and there is no turbulence. The proposed work is intended to obtain information about the mechanism of formation, rate of occurrence and the evolving shape of solitary waves; and quantitative aspects of the detailed events of the liquid removal process that can be used to verify a general predictive theory.

INTRODUCTION

Atomization of liquids in gas-liquid or liquid-liquid flows is one of the basic processes that determines the configuration of the phases and the overall behavior of the flows. Here we are defining atomization as the removal of liquid droplets from a flowing layer of a more viscous phase by shearing action of the (necessarily) faster-moving, less-viscous phase. For the air-water system, photographic experiments by Woodmansee and Hanratty [1] and Whalley et al. [2] have directly linked atomization to large waves -- liquid is removed by some mechanism from the crest of large solitary or roll waves. Preliminary work shown below for a mineral oil - water system exhibits the same mechanism. The primary questions about atomization to be addressed in our research are: how quantitative aspects of atomization (e.g. drop size and rate) change as viscosity, density and flow ratios, orientation and the presence of gravity are varied and which fundamental theory is needed to accurately describe atomization and allow prediction for situations outside the available range of data. Because atomization occurs at the crests of solitary waves, the behavior of such waves is of fundamental importance.

Atomization rates are an important issue in the design and operation of many industrial devices. Fore and Dukler [3] state that up to 20% of the pressure drop is from the atomization and deposition process. A stable oil film is needed on the walls of hydrocarbon transportation pipelines to protect the pipe from corrosion caused by CO_2 combined with condensed water. For pipelines with large gas-liquid flow ratios oriented close to horizontal sufficient atomization is needed. Numerous chemical processing operations rely on emulsification or atomization to create the interfacial area necessary for efficient reaction or contacting. Phase mixing is typically effected by agitation or pumping through nozzles. However, both of these processes are relatively inefficient. A fundamental study of the atomization mechanism can hence allow us to optimize these existing processes or suggest a more efficient new process, such as shearing a two layer configuration.

Figure 1 shows a comparison of solitary waves for air-water in a 1.27 cm tube taken during μ-g aircraft flights by Dukler and coworkers. If these are compared to waves in vertical annular flow on earth by Schadel and Hanratty

[4] (figure 2) or in our horizontal channel (figure 3) by Peng et al [5], it is seen that the wave amplitude to substrate ratio is much larger for μ-g. This is evidently because of the lack of uniform gravity that acts to drain liquid from waves in any flow geometry. Consequently based on the Woodmansee and Hanratty [1] mechanism, it is expected that atomization will occur more readily under microgravity conditions. As such, it becomes a fundamental consideration for the design of two-phase flow devices in spacecraft, space stations and lunar bases.

The importance of knowing the fraction of liquid entrained in gas-liquid flows has been recognized for many years. Studies originally focused on measuring the entrained fraction and developing empirical correlations (e.g. Dallman et al., [6] ; Asali et al., [7];). However as explained by Schadel and Hanratty [4], a better approach is to measure and correlate the atomization and deposition rates separately. Unfortunately, this still has not produced a general predictive relationship valid for all flows. This is perhaps because their correlations do not reflect the fundamental mechanism.

This paper describes some preliminary results that are intended to lead to verification of the mechanisms of liquid atomization by a gas stream or an immiscible liquid flow and to provide predictive capabilities for the widest possible parameter range. Experiments have been done for a two-liquid system in our rotating two-liquid Couette device and in an oil-water channel flow.

EXPERIMENTAL RESULTS

Figure 4 shows our density-matched, two-liquid rotating concentric cylinder device that can provide wave behavior that is not limited by the length of contact of the two phases. Some experimental details are given in Sangalli et al. [8] and an extensive description will be available in a forthcoming publication. The two fluids used for the experiments are Dow 710, which is a phenylmethyl polysiloxane fluid and a mixture of ethylene glycol, water, and Pink Bismuth – an Osco® brand upset stomach remedy. The Pink Bismuth is used as a source of refractive particles. The viscosity and density of Dow 710 are 0.555 Ns/m^2 and 1110 kg/m^3 respectively. The viscosity and density of the ethylene glycol solution are 0.0151 Ns/m^2 and 1108 kg/m^3 respectively. Dow 710 is loaded on the outer cylinder after the ethylene glycol mixture has been added to the channel.

We use several lighting techniques to probe the experiment -- white light, a vertical plane of laser light, and a horizontal laser sheet. The two laser methods provide useful quantitative data that direct visualization with white light does not allow.

Figure 5 shows a map of wave behavior for conditions where the depth ratio is such that the positive growth region for wave modes always extends from zero wavenumber up to a cutoff determined by the rotation rate. It is seen that periodic waves occur at low rotation rates for all depth ratios and that waves become more irregular as the rotation rate is increased. The occurrence of short wavelength, steady periodic waves for a range of conditions where long waves are unstable is quite surprising and important. In both the falling film problem that we studied earlier (Chang, [9]), where the shape of the growth curve is always similar the ones for figure 5, and gas-liquid channel flow (McCready and Chang, [10]) which also has the same growth curve at high gas flow, the long distance dominant disturbance is always a solitary wave or roll wave. Apparently, at low shear rates there is enough nonlinear stabilization in these two-liquid flows to prevent the long wave modes from growing. This may be caused by direct interaction between long and short waves similar to what is observed at low shear in gas-liquid channel flow (Jurman et al., [11]). At higher rotation rates, solitary waves seem to evolve from periodic waves. Because the number of solitary waves in the device is always less than the original number of small amplitude periodic waves, solitary wave formation must also involve some type of energy transfer mechanism between short and long waves. These examples underline the importance of understanding interactions between long and short waves. In the context of the current interest of two-phase flow in space, they suggest that even without gravity stabilization, a stratified state that does not suffer from atomization could exist. Thus, although previous studies have not reported stratified flow, it could occur -- perhaps in a small passage heat exchange device at a very inopportune time.

Figure 5 indicates that atomization occurs at sufficiently high rotation rates. The waves that occur in this range are irregularly-spaced large-amplitude waves. Our preliminary work has not allowed us to clearly discern the mechanism behind the formation of these waves and the subsequent atomization phenomenon because we need more light intensity to get sufficient video resolution. However there is no doubt that atomization occurs from the large solitary waves whose amplitude and separation can be precisely controlled by the experiment.

Figure 4 shows the cross-section another geometry that we have constructed specifically to demonstrate the mechanism of atomization. The channel is 1 cm high by 14 cm wide by 2.3 m long. The concurrent oil-water channel flow is operated so that the oil-water interface is imaged directly from the top. The oil and water have a curved interface and the oil is confined to a portion of the top wall. We have been able to get some dramatic video of oil droplets being formed by shearing water. When the water shear is significant, large semi-periodic waves form and travel along the interface. Figure 7a shows that if the shear is still higher, the crest becomes elongated. Figure 7b shows the later stage of the snap-off process. In this experiment, the oil waves are completely surrounded by water, they are not touching the top wall. For this geometry a shear instability must initiate the waves, growth is probably caused by a Bernoulli effect, and the actual pinch off by a combined capillary and shear instability. The size of the drop is determined by the size of the streamer from the crest. Note that even if the geometry of the base flow is parallel, such as in Woodmansee's experiment, drops will still be sheared from fingers of liquid because the waves that occur at very high shear have significant transverse variation; there will never be wide sheets of liquid sheared from the crests of waves. Thus our demonstration experiment is close to the general system that will be studied.

A final preliminary experiment is intended to directly probe the behavior of waves that are the precursors of solitary waves. The ultimate intention of our work is to actively control these waves. In the two-layer Couette cell, the initial transition from a flat film is supercritical and in agreement with linear and weakly nonlinear theory (Sangalli et al., [8]). Figure 8 shows a sample experiment where a weak oscillatory component is added to the steady rotation. The oscillation amplitude is 0.25 cm and the frequency is 6 Hz. It is seen that either with or without oscillation a supercritical transition occurs. The oscillation in this experiments and others that we have tried destabilizes the waves. This is consistent with the argument that the oscillation is adding energy to the flow which causes more wave growth.

DISCUSSION

Figure 5 shows that atomization is a likely consequence for a flow at sufficient shear. However the non monotonic behavior indicates that onset of atomization is not a simple function of shear rate. Further, no attempt was made to quantify the extent of atomization. Figure 7 shows that it will be crucial to incorporate the mechanism into procedures for predicting atomization rates. The atomization process involves instability and growth of waves on the base state and then a further instability of the large wave structure. The formation of solitary or roll waves, commonly associated with atomization, and the waves of figure 7 are certainly governed by nonlinear process that are presently understood only for very simple model equations (e.g., see [9]).

Development of a complete understanding of the atomization process will take advances on a number of fronts. Figure 8 shows an example of our efforts in the weakly- nonlinear region where we are using oscillations to better understand the wave growth and saturation mechanism. Although we have not yet found a region where waves are stabilized, theories suggest that certain ranges of oscillations should depress wave formation. We hope this will ultimately lead to wave control that could alter pressure drop or atomization.

ACKNOWLEDGMENTS

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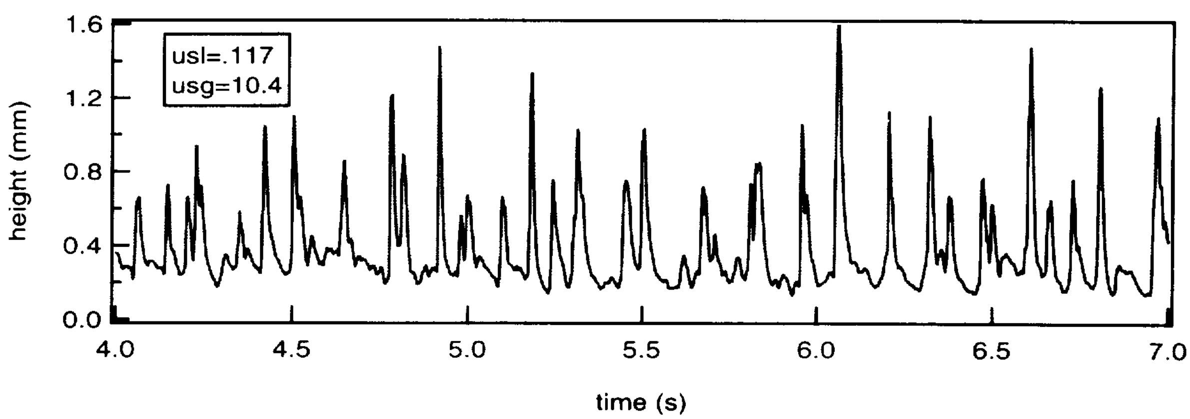


Figure 1. Wave tracings for air-water in a 1.27 cm pipe under μ-g. Data from NASA Lewis Lear jet flights supervised by A. E. Dukler.

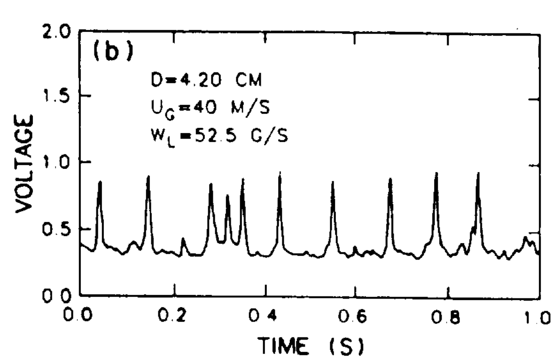


Figure 2. Wave tracings in vertical annular flow by Schadel and Hanratty (1989)

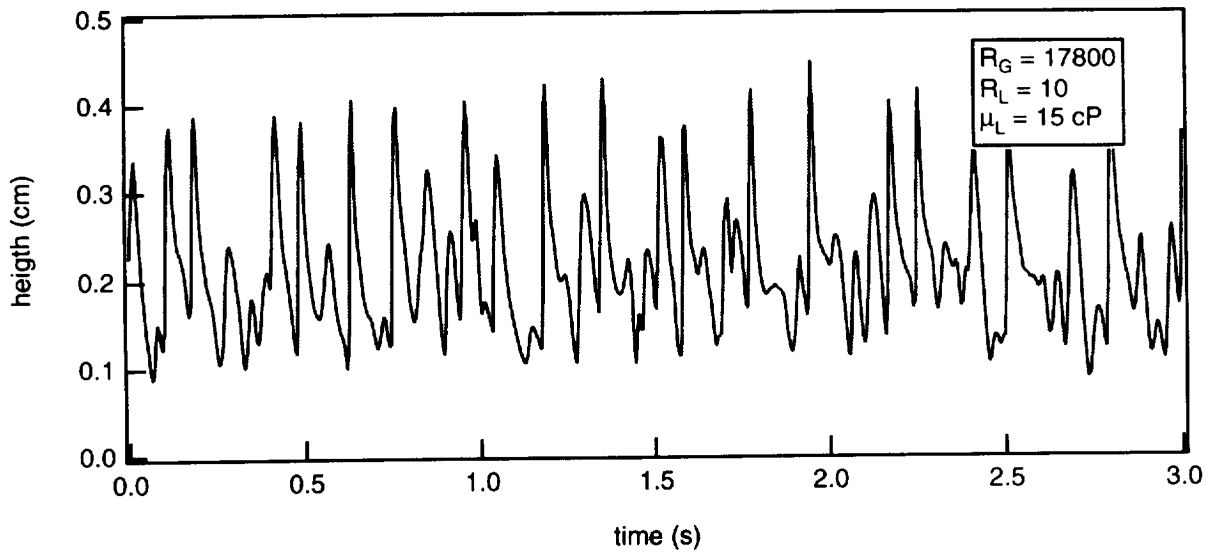


Figure 3. Solitary waves in a horizontal gas-liquid flow in earth gravity

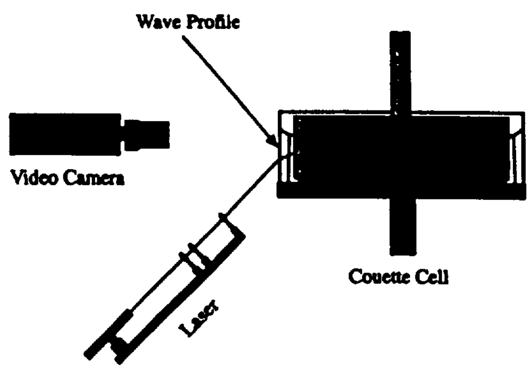


Figure 4. Two-layer Couette experiment with horizontal laser shown.

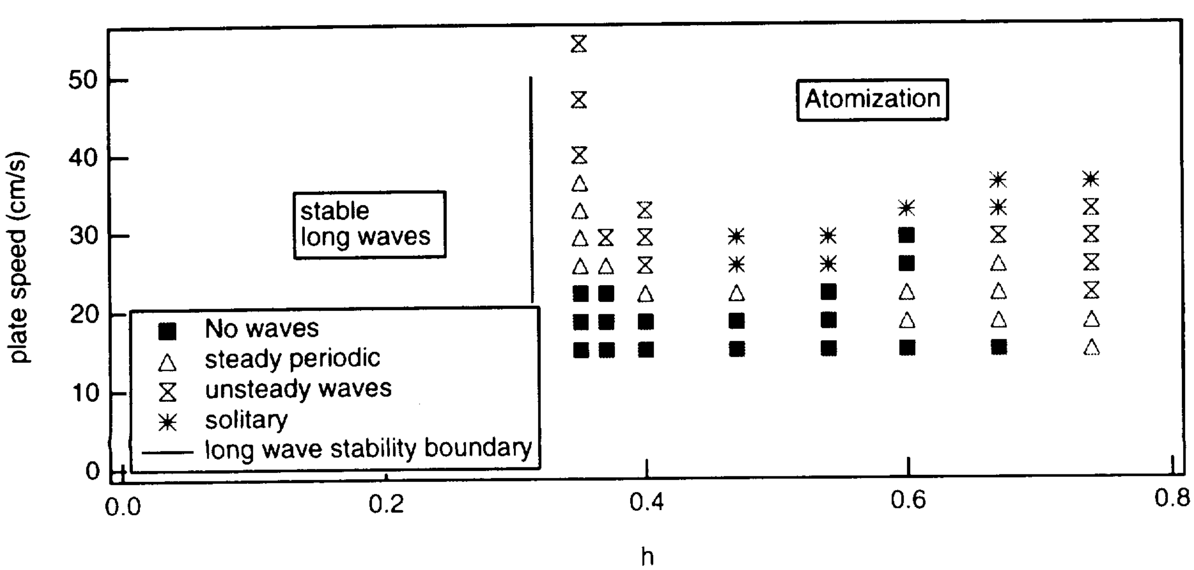


Figure 5. Wave regime map for the two-layer Couette experiment. Atomization occurs at high rotation rates.

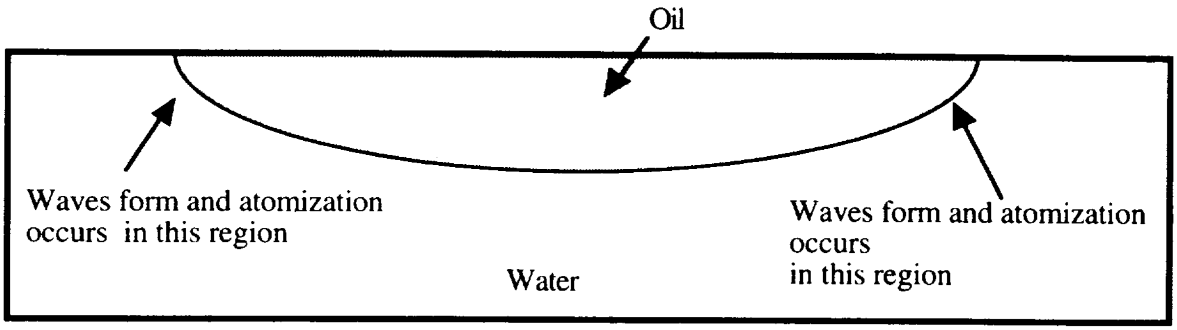
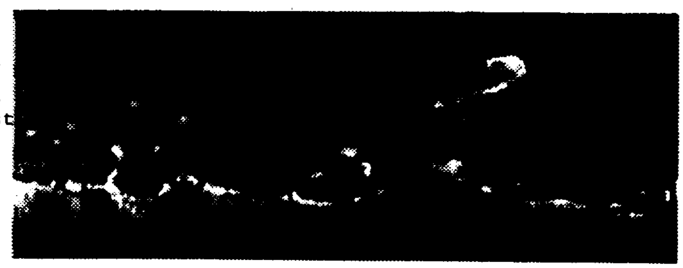


Figure 6. Cross section of cocurrent oil-water flow that demonstrates the mechanism of atomization.

Figure 7a. Large wave in oil water flow

Figure 7b. Late stages of liquid removal from wave crest



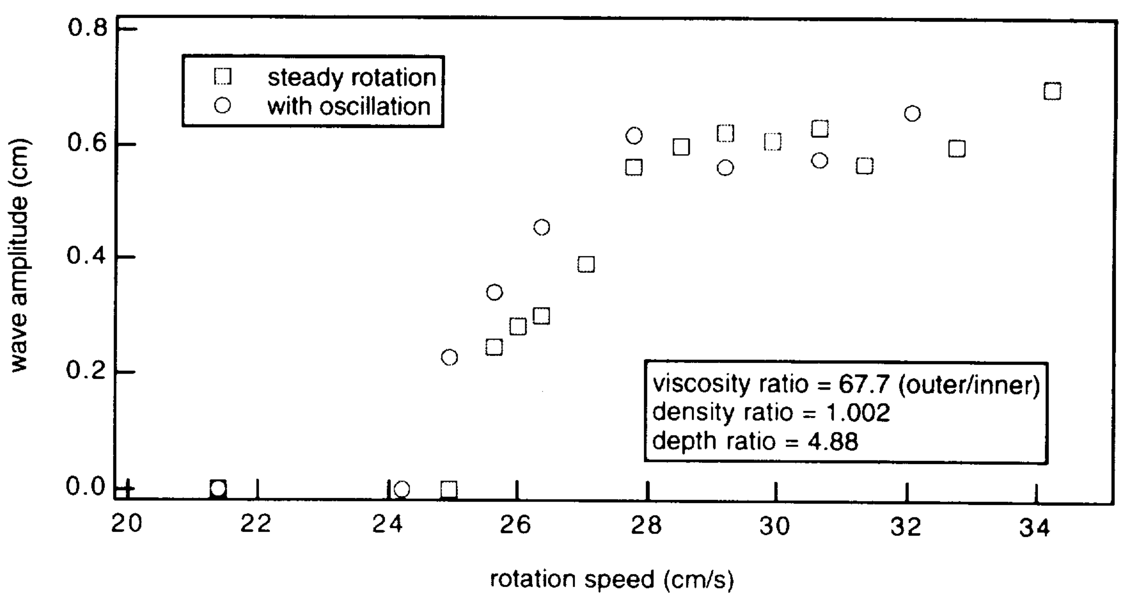


Figure 8. Wave amplitude as a function of rotation rate. Weak oscillation slightly destabilizes the waves.