INTERFACIAL WAVE TRANSITIONS IN LIQUID-LIQUID FLOWS AND INSIGHT INTO FLOW REGIME TRANSITION

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ABSTRACT

Measurements of developing interfacial waves on oil-water channel flows show that long wave modes form and grow to large amplitude even though they have much smaller linear grow rates than shorter waves. There is evidence for a "triggering" of these long waves by interaction with much shorter waves, although most of the energy for wave growth comes from the mean flow. Thus linear instability of these long waves is a necessary condition for their formation and consequently, for flow regime transitions from a stratified state. However, experiments in a rotating Couette flow show regimes of no wave growth, even when long waves are unstable. The apparent reason for this is given by numerical integration of the equations that describe weakly-nonlinear wave modes at the interface. The simulations show a cascade of energy from long to short waves and no preferred wavenumber in the spectrum.

INTRODUCTION

Multifluid flows exist in oil wells, oil production and transportation pipelines, heat exchangers, gas-liquid reactors with solid catalyst and various other process piping and vessels. An important emerging issue for multifluid flow research will be how to best solve the contacting/mass and heat transfer problems that will greatly increase, as a new generation of "molecularly-engineered" catalysts developed with much higher dispersion of active metal and more elaborate possibilities of interconnection of pores on different scales. However, given the current uncertainty that exists in the simplest case, gas-liquid flow in pipe, these new problems may be difficult to solve.

Even in light of the need to understand multifluid flow on small scales, their defining characteristic, in channels, pipes and even packed beds is the strength of the *largest* scale disturbances present. For gas-liquid pipe flows, where 6 different flow regimes are possible, slug flow [1] is the regime with large coherent disturbances cause large pressure fluctuations [2] and variations in the gas and liquid flow rates that can affect process equipment. For gas - liquid packed bed flows, the corresponding region is the pulsing flow regime[3], for which the large disturbances have been shown to have the beneficial effect of increased mass transfer rates that can favorably affect the reaction outcome[4].

The existing problem in the prediction of large disturbances leading to slug formation is there are multiple mechanisms that are at work [5] and slugs can form directly from growth of waves on flat layers or by coalescence of several large rollwaves. The standard techniques for the prediction of slugs are various linear stability theories, based on different assumptions and some work that addresses the stability of a slug once it forms. Figure 1 shows several such models. It is readily seen that significant disagreement exists between the different procedures for slug prediction -- even those that are based on the same premise of unstable long waves. If these models are plotted for a model oil-gas flow at 100 ATM in a larger pipe, even bigger disagreement exists. From these results it can be concluded that considerable uncertainty exists in the prediction of slug flow for engineering purposes.

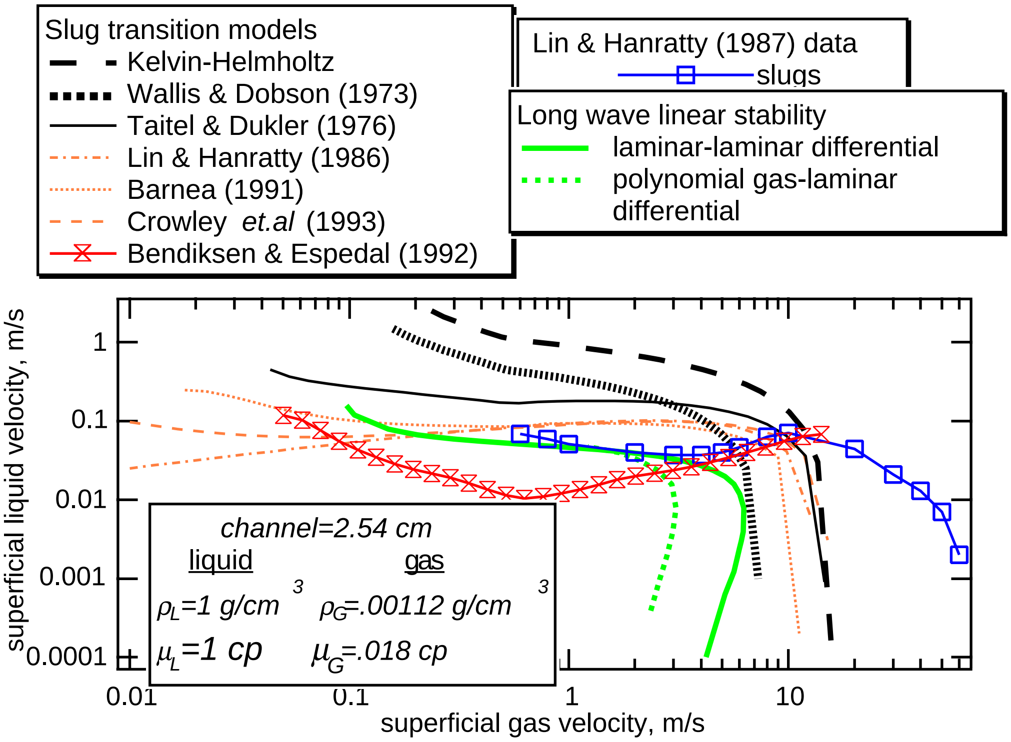

Figure 1. Different slug transition models for air-water in a 2.54 cm, horizontal pipe.

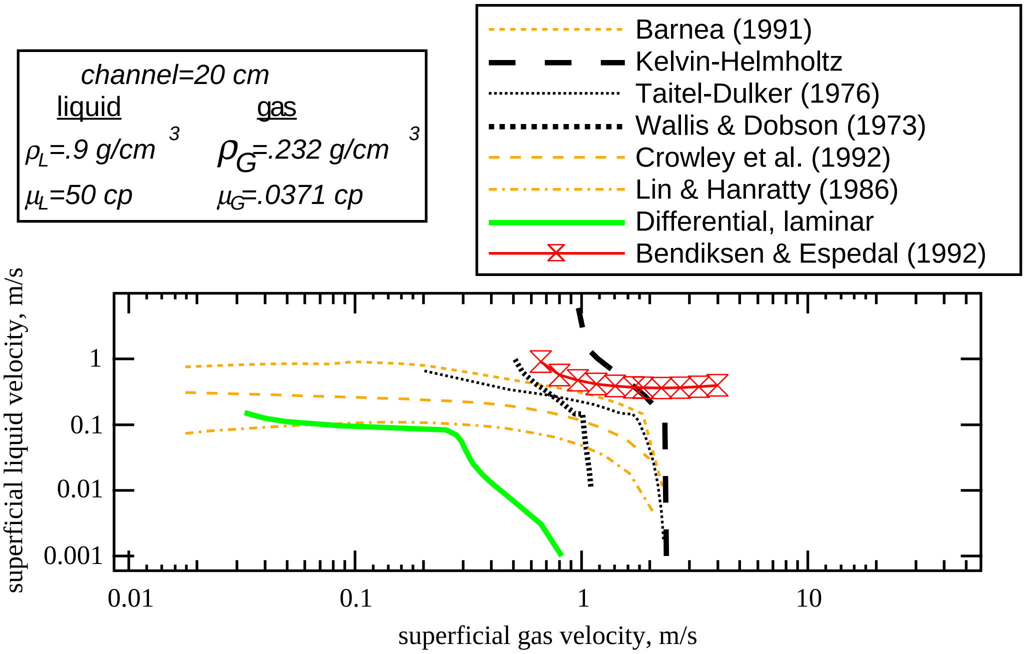

Figure 2. Different slug transition models for oil-gas in a 20 cm horizontal pipe at 20 ATM.

The specific problems addressed in this paper are the mechanisms of wave development on a two-layer stratified flow. Experiments are presented which show that the presence of a long wave instability does not mean that large disturbances will form -- casting doubt on the use of linear stability as a predictive tool for the transition from stratified to slug flow. The development of waves in an oil water channel flow is examined, as a function of distance, showing the development of a long wave peak after the more unstable short waves appear. Numerical simulation of the weakly-nonlinear mode equations is used to provide an explanation of the observed experimental behavior.

EXPERIMENTAL SYSTEMS

Figure 3 shows a schematic of the oil-water channel that is used for the experiments. Data are obtained from visual and video observations and from conductance probes. The fluids are water, with Sodium Silicate added to improve its ability to wet the Plexiglas® channel and a light hydrocarbon oil with a density of 0.88 g/cm^3 and a viscosity of 17.8 cP. More details about the flow system and its construction are included in a thesis by McKee[6].

Figure 4 shows the optical system that is used to obtain data in the oil-water channel flow. The behavior of the interfacial waves is obtained by measuring the time varying wave slope with an optical refraction technique. A laser beam is split into 2 vertical beams a distance db apart and focused onto the interface. The beams are refracted at the interface according to Snell's law due to the instantaneous wave slope. The refracted beams are focused onto position sensing detectors, which provide the displacement of the refracted beam in x,y coordinates from its initial vertical position. From the geometry of the optics and the location of the refracted beam, a time series of the interfacial wave slope is created for each of the two beams. The signals from the two beams can be used to measure the wave velocities.

Experiments were also done using two matched-density liquids in a rotating Couette device. Details have been published previously[7,8].

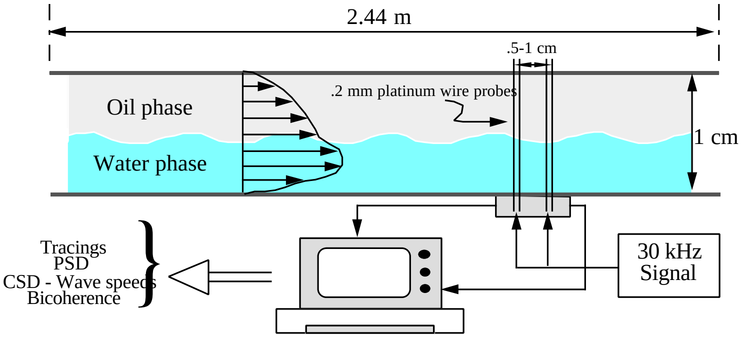

FIGURE 3. OIL-WATER CHANNEL FOR STUDYING INTERFACIAL WAVES

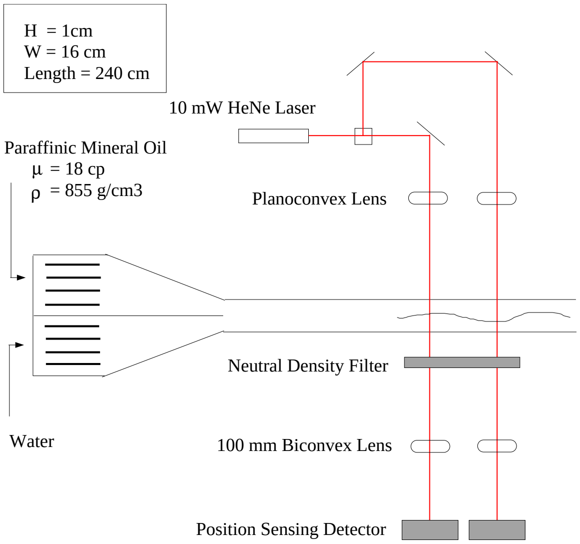

FIGURE 4. SCHEMATIC OF LASER-SLOPE DATA ACQUISITION SYSTEM FOR CHANNEL FLOW

THEORY

Theoretical analysis for this system is based on the complete two-layer Navier-Stokes equations and boundary conditions. The linear stability problem has been solved by Yih[9]and Blennerhassett [10] among others. The weakly nonlinear problem has been formulated with a multiple scales technique by Blennerhassett [10] and an eigenfunction, center manifold approach by [11] and [12]. Instead of confining our analysis to the Stuart Landau equation [12]

$$\frac{\partial A}{\partial t} = L(\lambda)\, A + \beta\, |A^{2}\, |A| \quad , \qquad [1]$$

where A is the complex wave amplitude, L(λ) is the linear eigenvalue, β is the Landau coefficient,
we do not use a center manifold approach to simply the equations. The result is then a system of many mode equations of the form

$$\dot{A}_{nl} = L_{nl}A_{nl} + \sum_{p,q,r,s} \vartheta_{nl,pr,qs}A_{pr}A_{qs} + \sum_{p,q,m,r,s,z} \xi_{nl,pr,qs,mz}A_{pr}A_{qs}A_{mz} \qquad [2]$$

where the nonlinear interaction coefficients, for the quadratic terms, v and the cubic terms, ξ, are functions of liquid depth and wavelength and weaker functions of the degree of shear and the shape of the velocity profile. These equations are solved by numerical integration. Further details on the derivation of these equations and their solution are given in a paper from our group[13].

RESULTS

Figure 5 shows our previous data [7] that indicate regions of the rotation rate- depth ratio space where long waves are linearly unstable and no waves appear. Thus according to the premise of most slug formation theories, large disturbances are expected in this region. Even though this experiment is not channel flow, it calls into question the idea of using instability of long waves as a general criteria for flow regime transition.

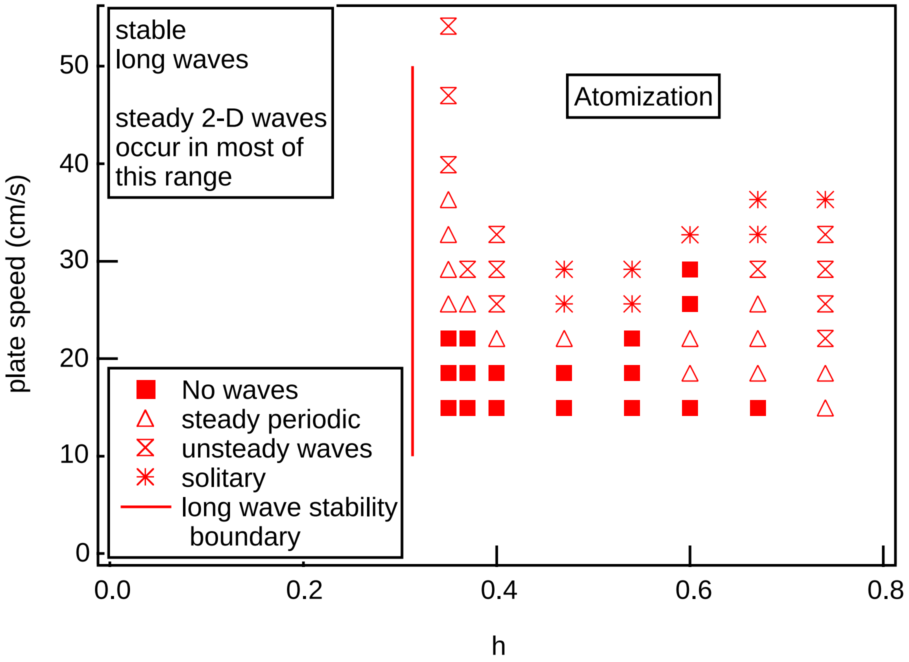

Figure 5. Wave regime map of a rotating Couette flow (left), Simulated spectrum for conditions of h= 0.4, U = 25 cm/s.

A movie of the simulations at h = 0.4 and U = 25 cm/s is available at http://www.nd.edu/~mjm/ specsim.mov. It shows that as the waves grow, there is a cascade of energy from long to short waves, that acts to stabilize the formation of long waves. Further the apparent absence of any waves can be possibly be attributed to the lack of preferred wavelength. Figure 6 shows these spectra at different times during the simulation. At the shortest time, the spectrum matches the linear growth curve. At all longer times there is a continual broadening of the spectrum. However, there is never a clearly-defined wavelength that could be visible in experiments. All of the apparent peaks oscillate in magnitude.

Figure 7 shows wave spectra for a developing oil-water channel flow. It is seen that at the first two positions, the spectra match the predictions of linear growth. However at 60 cm, the spectrum shows a number of distinct peaks that are involved in nonlinear interactions. This is confirmed by the bicoherence spectrum of figure 8. Bicoherence spectra [14] show the strength of quadratic

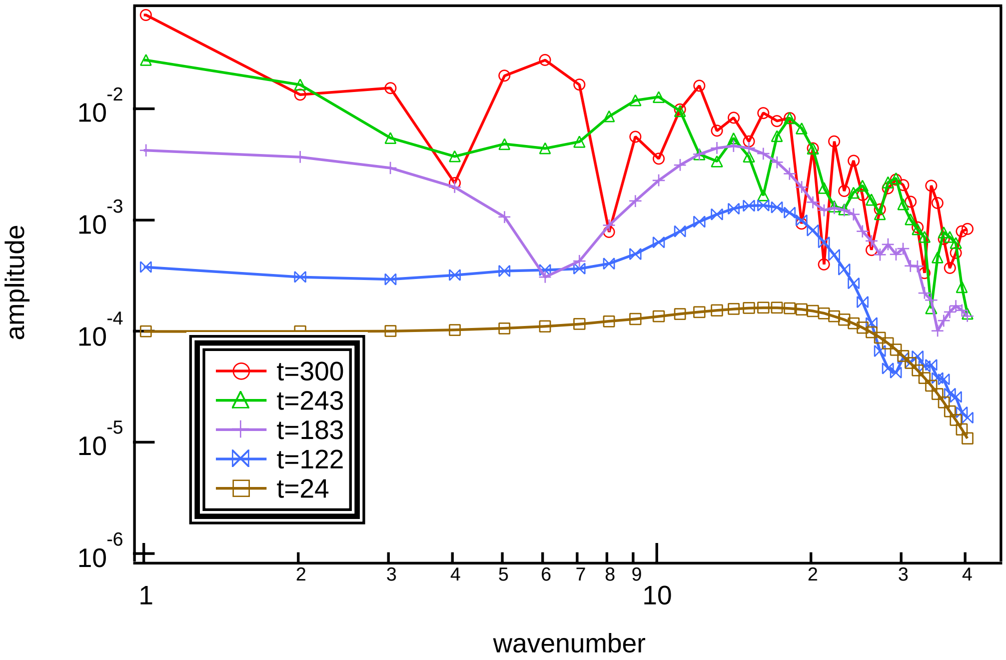

Figure 6. Amplitude spectra for Couette flow. At longer times there is no preferred wavenumber.

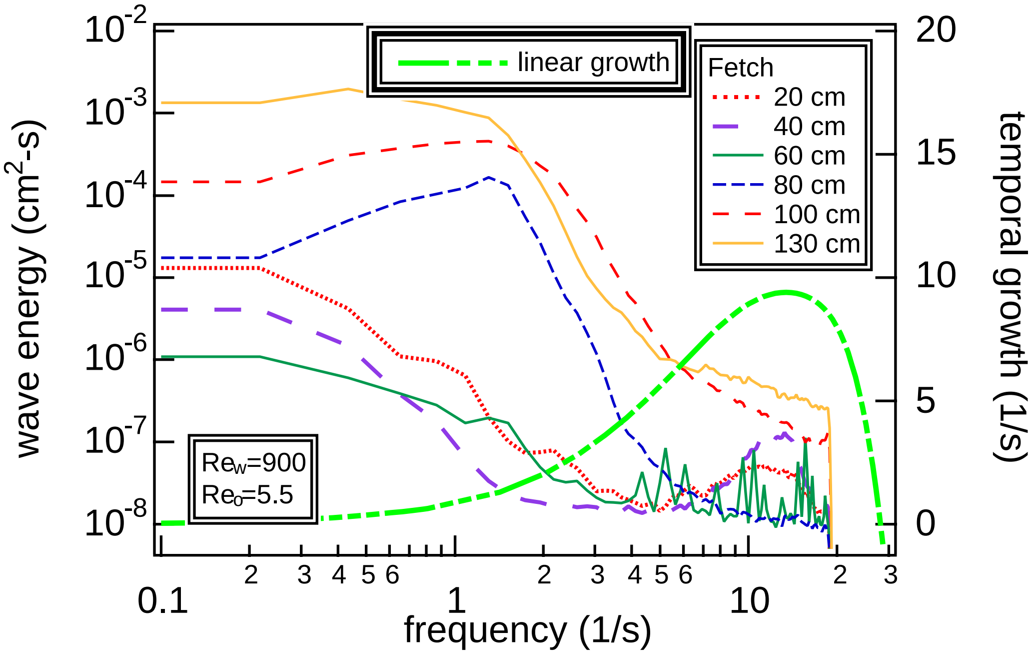

Figure 7 shows the spectra of a developing oil-water channel flow for Rew=900 and Reoil=5.5. The linear growth curve is also shown.

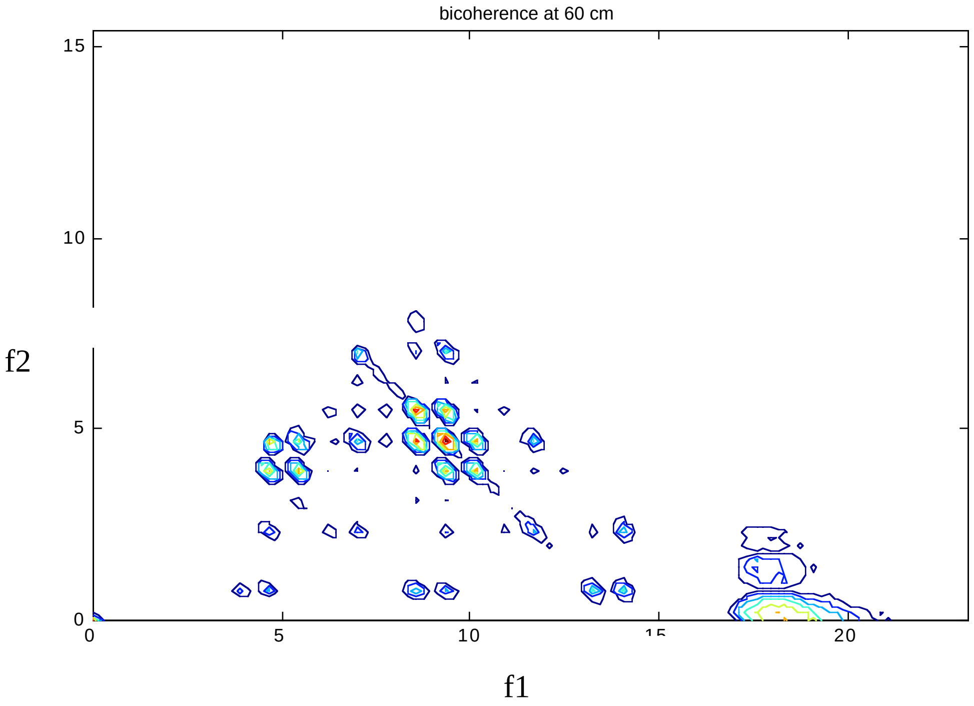

Figure 8. Bicoherence spectrum for oil-water flow of figure 7 at 60 cm. Significant coherence exists between short-short (5,10 Hz) and long short (18,1 Hz).

interactions of the form f1 + f2 = f3. Perfectly coherent modes will have a value of unity. Figure 8 shows that there are interactions between some distinct peaks around 10 Hz and their overtones (f1 = f2) (that are not shown on the power spectra of figure 7) and also with their corresponding subharmonics around 5 Hz. For this subharmonic, f1= f2= 5 Hz. A very strong interaction is seen between a wave mode of about 18 Hz and 1.5 Hz. This is probably a *difference* interaction, f1-f2 = f3, so that the other mode involved is probably about 16.5 Hz. This long-short interaction may be responsible for triggering the formation of a low frequency mode, 1.5 Hz, that is seen to growth substantially between 60 and 80 cm and which completely changes the character of the spectrum.

DISCUSSION

The experiments and simulation presented above provide insight into several different issues. First, figures 1 and 2 show that current predictive methods for the transition to slug flow differ greatly and probably none can be trusted to give reliable results. Second, the presence of no waves in regions where long waves are unstable, calls into question any methods for which long wave stability is the sole criterion for transition. It does appear, however, that long wave stability is a necessary condition for instability. The spectral simulations for the Couette flow suggest that a reason for the absence of visible waves is the lack of a persistent dominant wavenumber. This statement has not been confirmed and it is still possible that imperfections on the experiment may be the reason for the lack of observed waves.

The spectra of developing oil-water flows show that linear growth is followed by nonlinear interactions that can cause subharmonics or trigger low wave modes. These low modes can be precursors of roll waves and slugs. Subharmonics have also been implicated in the transition to slug flow[15].

These results suggest a need for improved procedures for prediction of regime transition that account for the nonlinear processes. They also suggests methods for controlling the transition and perhaps picking the frequency of the large disturbances -- by controlling the frequency of shorter waves that trigger these long wave modes.

Finally because the large disturbances that occur in packed-bed flows[3], pulses, are very similar to slugs in pipe flows -- but not as easy to study -- it could be profitable to look for analogies between the two different systems to better understand the reaction processes that are performed in gas-liquid catalytic reactors.

ACKNOWLEDGMENT

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