1995108152
350279
6p
N95-14566

TWO-LAYER VISCOUS INSTABILITY IN A ROTATING COUETTE DEVICE

Christopher Gallagher,
Tom Kropnewicki,
David T. Leighton, and
Mark J. McCready

University of Notre Dame
Department of Chemical Engineering
Notre Dame, IN 46556

ABSTRACT

A novel experiment to study the interfacial shear instability between two liquids is described. Density-matched immiscible liquids are confined between concentric cylinders such that the interface is parallel to the cylinder walls. Interfacial waves that develop because of viscosity difference between the shearing fluids are studied as a function of rotation rate and depth ratio using optical techniques. Conditions of neutral stability and the most unstable wavenumber agree reasonably well with predictions from linear stability analysis of the Navier-Stokes equations. Illumination using laser sheets allows precise measurement of the interface shape. Future experiments will verify the correctness of weakly nonlinear theories that describe energy transfer and saturation of wave growth by nonlinear effects. Measurements of solitary wave shapes, that occur far above neutral stability, will be compared to similar measurements for systems that have gravity as an important force to determine how gravity effects large disturbances. These results will be used to interpret slug and annular flow data that have been obtained in other μg studies.

INTRODUCTION

Cocurrent flows of immiscible fluids are found in process flows, (e.g., condensers, oil-water separators, iron-slag separators), hydrocarbon production and transportation pipelines and there may be future opportunities to replace contacting devices that rely on emulsification (e.g., liquid extractors) with separate flowing phases that have high interphase transport coefficients. Critical information necessary for design and operation of these devices is whether the phases will remain separate (perhaps due to density differences) or if mixing will occur. While prediction of the phase configuration has been done using flow maps [1] of *dimensional* variables and stability analysis has been done with constitutive criteria [2,3,4,5], the validity of these procedures is generally confined to conditions close to the conditions of the experiments on which they were based. Further, the true predictive capabilities of these methods are lacking. If a base state with separate phases can be defined, a rigorous linear stability analysis that employs numerical solutions of the governing equations [6,7] can be done to determine if the base state is stable. While linear stability analysis can predict the conditions when waves will form and grow with distance, nonlinear theories are needed to determine if saturation of these waves will occur [8,9]. These rigorous nonlinear theories are valid only if the wave slope remains small; if the waves get too large, no predictions can be made. Consequently, experiments are needed to determine the long distance evolution of disturbances. Unfortunately, conduits available in laboratories are often too short and industrial pipelines too irregular to determine definitively what the long distance state of a linearly unstable flow is.

To solve this problem, we have devised a new experiment that uses a two-layer flow of density matched fluids confined between concentric cylinders. The interface is parallel to the cylinder walls and rotation of the outer cylinder, for fixed inner cylinder, induces shearing that can lead to instability. The waves that form are completely analogous to interface waves formed by a shear flow in a flat channel. For the rotating device these have crests that are parallel to the rotation axis and exhibit interface deformation in the radial direction (r) that is initially periodic in the direction of rotation (θ). This device can simulate extremely long distance evolution of disturbances by simply waiting a sufficiently long time. For example, experiments shown below indicate that waves with significant amplitudes will form only after several minutes at rotation rates large enough to cause instability. This corresponds to over 100 meters of length -- a distance not usually available for a well-controlled experiment.

Interfacial wave growth curves for systems such as gravity driven films, pressure driven pipe or channel flow and two-layer Couette flows have two distinct shapes. Figure 1 shows temporal wave growth curves calculated numerically [10] using a two-layer Orr-Sommerfeld analysis and full linearized boundary conditions. In figure 1a the region of positive growth is bounded away from 0 wavenumber. Figure 1b shows the second shape where the growth rate has a maximum away from 0 but is positive all the way down to 0 once any wavenumber becomes unstable. The primary question suggested is: what generic differences are there in the very long time evolution of waves for the two different types of growth curves? Previous work [11] suggests that wave modes can be generated in linearly stable regions by nonlinear interactions, but it is not clear if they stay at small amplitudes or grow into the dominant waves. Gravity driven films, once unstable, always look like figure 1b, channel flows can exhibit either of the two behaviors.

The two-layer Couette geometry changes from 1a to 1b as h, the ratio of the inner (less viscous film) layer thickness/gap thickness, is altered. Thus it is possible to compare the behavior of both types of growth curves using well-controlled long time experiments. In this paper we describe the device, the experimental procedures and give some preliminary results on regions of instability and wavelengths of observed waves.

EXPERIMENTAL

Wave measurements have been made in a rotating concentric cylinder test cell. The diameter of the inner cylinder is 19.50 *cm* and the diameter of the outer cylinder is 21.50 *cm* resulting in a gap thickness of 1.00 *cm*. The gap width is 5 *cm*. The cylinders are loaded into a Weissenberg rheogoniometer such that the inner cylinder is fixed, the outer cylinder may be rotated, and the axis is aligned with gravity. The concentricity of the cylinders is aligned to a tolerance of about 75 μm while the tilt of the cylinders is aligned to a tolerance of about 25 μm.

To perform measurements in our system, the outer wall is transparent to permit direct imaging of the interface. 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 2a is a diagram of the vertical laser setup. It shows a plane of laser light projected on to the interface at a large incident angle. The laser light is visible at the outer surface of the outer wall and at the interface. The distance between the two laser images is proportional to the fluid depth ratio. Further, the image on the interface is a profile of the interface shape. Figure 2b is a diagram of the horizontal laser setup. The horizontal laser set up is designed to show a wave tracing at a constant vertical position.

The two fluids used for the experiments whose results are presented here 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.

To map the stability boundary of our system, the velocity of the outer plate was set to about 0.05m/s and periodically increased until waves formed. The exact value of the initial velocity is dependent upon the stability of the interface. If conditions change much from the conditions when the fluids were density matched, larger velocities are needed to maintain the interface.

RESULTS AND OBSERVATIONS

The growth curves in figure 1 predict that waves will form if the rotation velocity is sufficiently large and become detectable after a sufficiently long time. Figure 3 is a plot of Reynolds number versus dimensionless inner film thickness. The three curves correspond to dimensionless growth rates of 0.0, 0.001, 0.015. The circles show the experimentally - observed onset of waves. For a height of 0.7, waves were observed very close to the predicted onset conditions. A growth rate of 0.001 corresponds to a time constant of approximately 5 minutes and a flow distance of 100 m! For smaller heights, a larger growth rate was required to observe waves. This may have because we did not wait long enough for waves to form, or it could be because nonlinear effects caused saturation at amplitudes too small to observe. Further experiments and nonlinear analysis are needed to resolve this issue.

Observed wavenumbers match well with the predicted fastest growing waves. Figures 4a-d are plots of the theoretical growth rate curves for the most unstable wave mode and experimental data. Wavenumbers for experimental data are depicted with a dashed line. Most of the stability points lie near the maximum growing wave number. The wavenumber for figure 4b lies closer to 1/2 the most unstable wavenumber. This could have been excited when the rotation rate was lower and thus the most unstable wave mode occurred at a lower wavenumber. This behavior has been seen in previous experiments with conditions such that the system was unstable for all Reynolds numbers. In those experiments, a small amplitude long wave was excited at a low plate velocity and grew in amplitude with increasing velocity. An alternative explanation is that there could have been nonlinear interactions that caused transfer of energy to lower wavenumber. Further experiments that carefully watch the time evolution of the wavenumber will be done to see which scenario is occurring.

CONCLUSIONS

Two-layer shear flow interfacial instability can be studied in the geometry of a rotating Couette flow that allows observation of wave evolution at times and (effectively) distances much longer with much better control than is possible in channel flows. Density matching of the fluids, necessary to create the vertical interface geometry, essentially removes gravity as an important force. By doing long time experiments, it is possible to examine the importance of modes near zero wavenumber that have much lower growth rates than shorter modes. These experiments will enable careful checks of nonlinear theories that predict energy transfer between modes and saturation of amplitudes at sufficiently long times. Direct white light imaging using a standard video camera allows measurement of the wavenumber and wave speed. The precise interfacial wave shapes, which are particularly important away from neutral stability where the shape is nonsinuous, can be accomplished using laser sheets to illuminate the flow cell. It is hoped that these measurements of nonsinuous waves will help to interpret annular and slug flow behavior that is observed in μg studies that have been done.

ACKNOWLEDGMENTS

This work has been supported by the NASA Microgravity Science and Applications Division under grant number NAG3-1398. The authors would like to thank Mr. Massimo Sangalli for allowing the use of his computer code that solves the two-layer stability problem for the Navier-Stokes equations.

REFERENCES

1. J. M. Mandhane, G. A. Gregory and K Aziz, Int. J. Mult. Flow, 1 (1974) 537-553.
2. Y. Taitel and A. E. Dukler, AIChE J., 22 (1976) 47-56.
3. D. Barnea, Chem. Eng. Sci., 46 (1991) 2123-2131.
4. D. Barnea, Int. J. Mult. Flow, 3 (1987) 1-12.
5. N. Brauner and D. M. Maron, Chem. Eng. Sci., 46 (1991) 1849-1859.
6. S. G. Yiantsios and B. G. Higgins, Phys. Fluids, 31 (1988) 3225-3238.
7. Y. Y. Su and B. Khomami, Journal of Computational Physics, 100 (1992) 297-305.
8. P. J. Blennerhassett, Proc. R. Soc. Lond. A, 298 (1980) 451-494.
9. M. Renardy and Y. Renardy, Phys. Fluids A, 5 (1993) 2738-2762.
10. W. C. Kuru, M. Sangalli and M. J. McCready, submitted to Int. J. Mult. Flow.
11. L. A. Jurman, S. E. Deutsch and M. J. McCready, J. Fluid Mech., 238 (1992) 187-219.

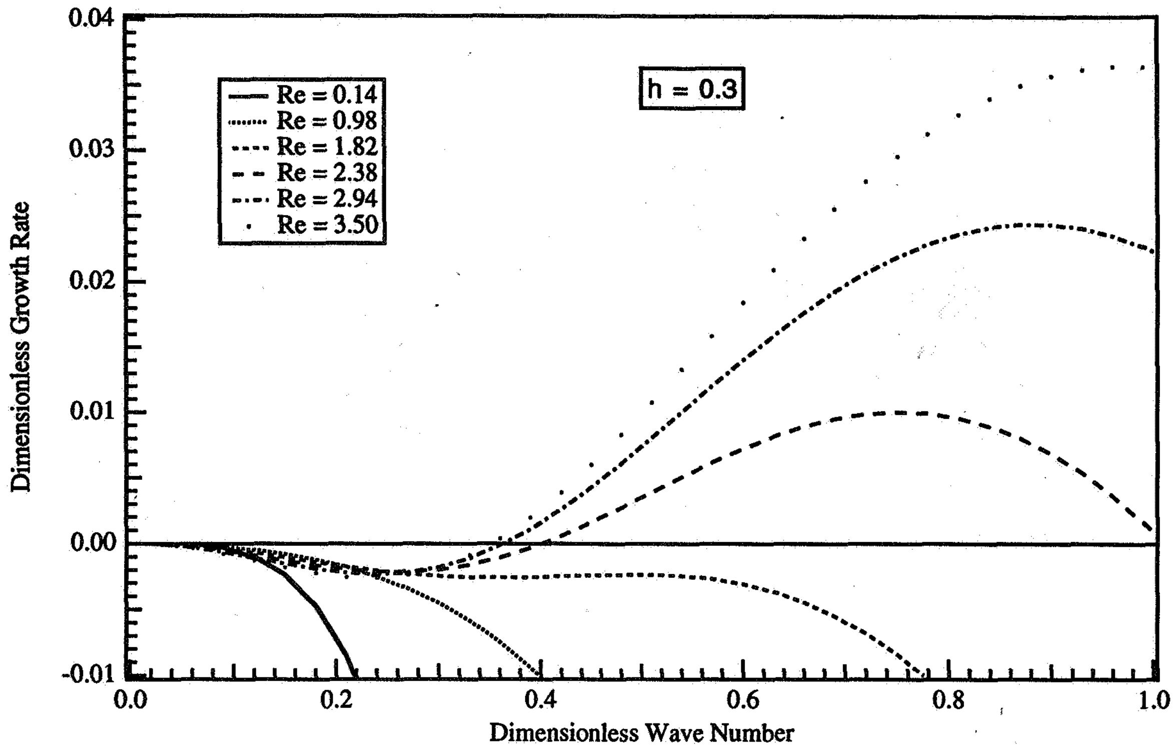

Figure 1a: Plot of growth rate versus wave number for conditions which can have positive growth bounded away from 0 wavenumber.

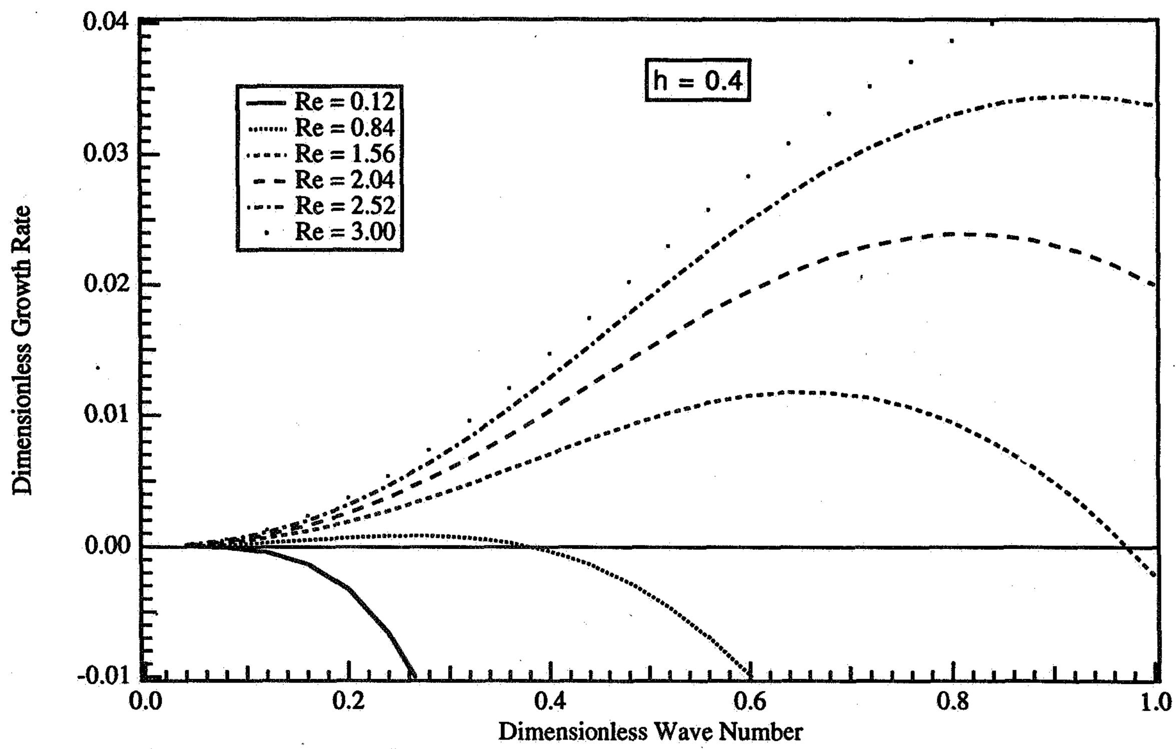

Figure 1b: Plot of growth rate versus wave number for conditions where unstable waves extend all the way down to 0 wavenumber.

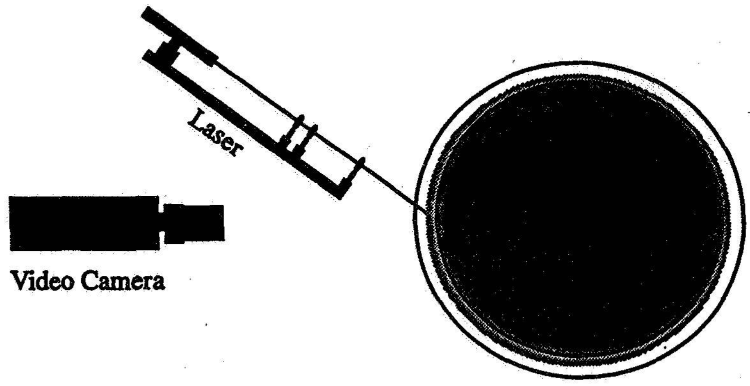

figure 2a: Vertical laser setup.

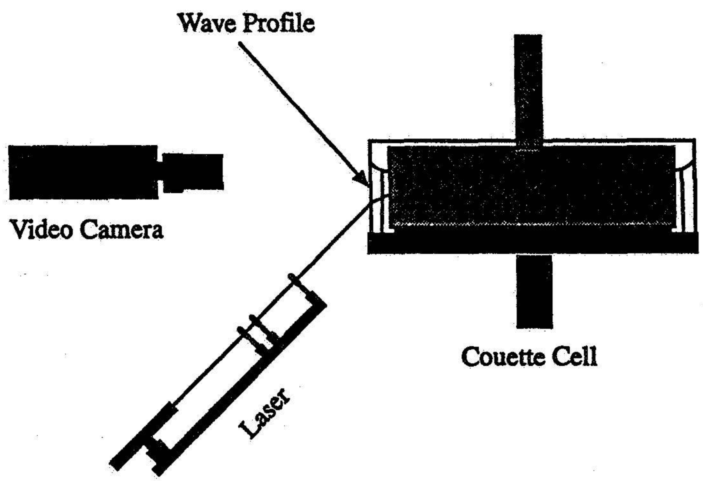

figure 2b: Horizontal laser setup.

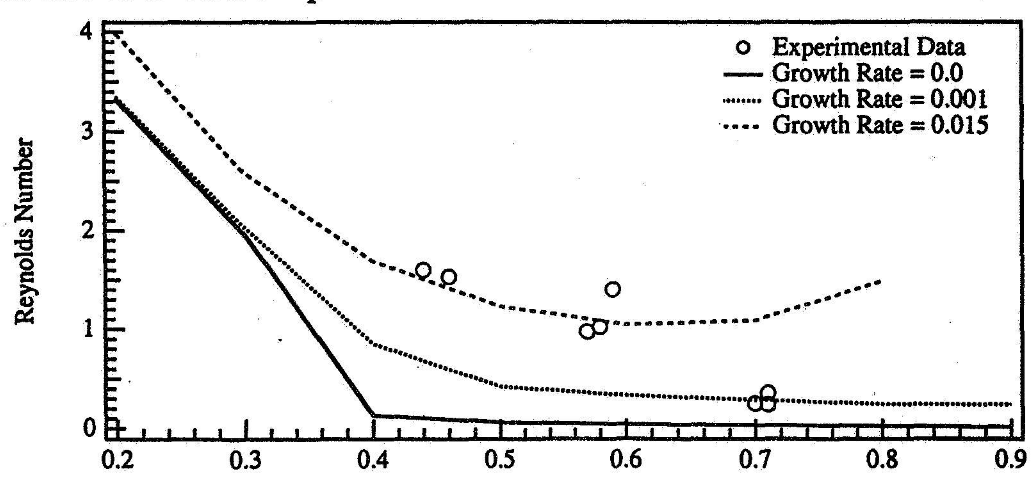

figure 3: Stability curves for three characteristic growth rates plotted with experimental data

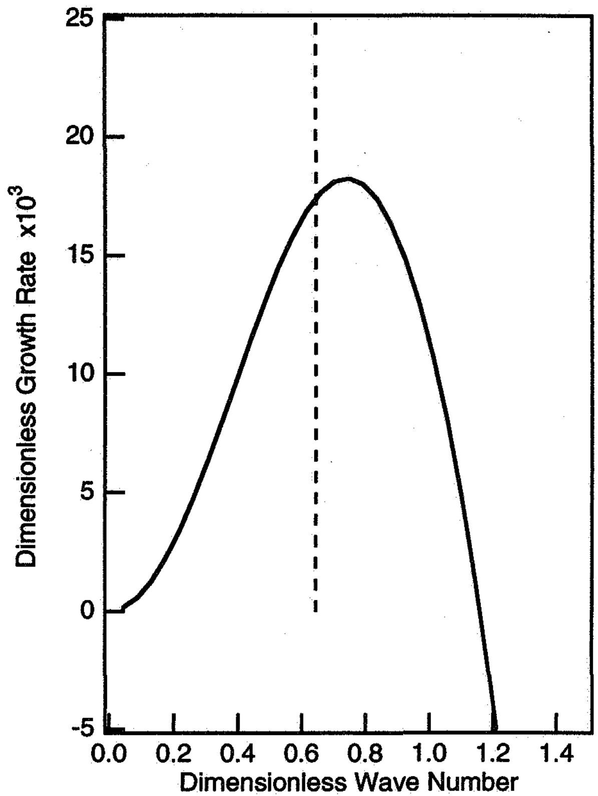

Figure 4a. h = 0.44, Re = 1.60

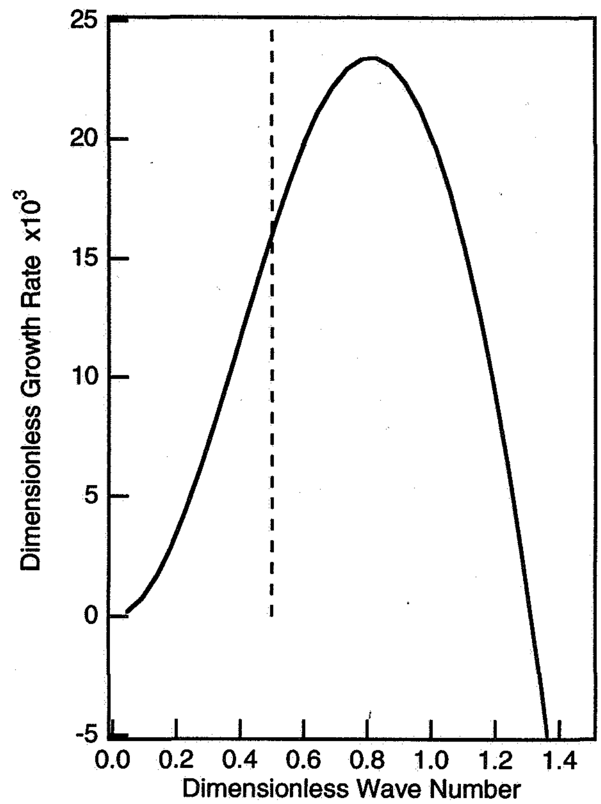

Figure 4b. h= 0.46, Re = 1.53

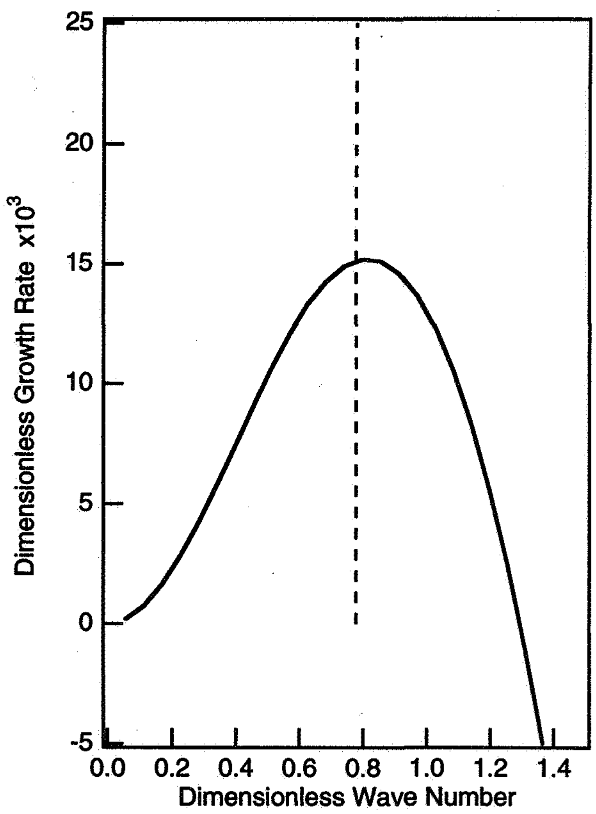

Figure 4c. h = 0.57, Re = 0.97

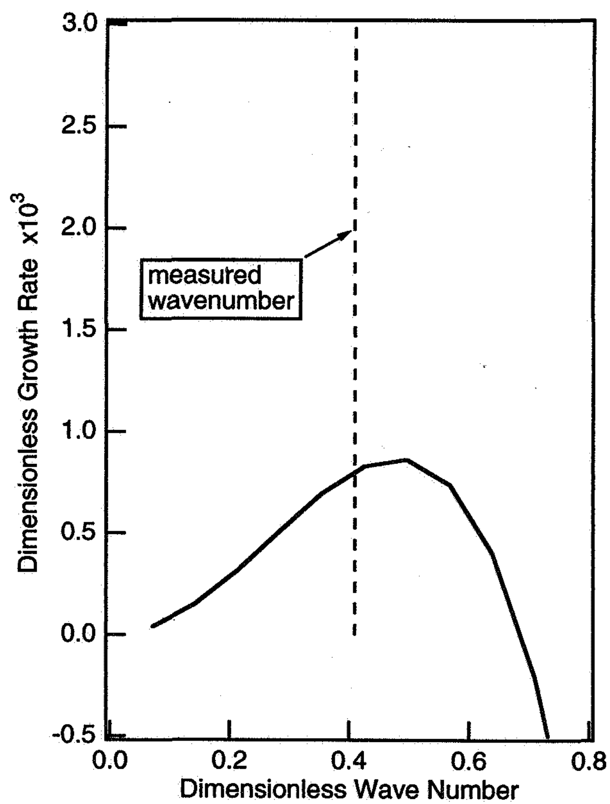

Figure 4d. h= 0.71, Re = 0.24