01 Jan 1973

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Recommended Citation

Johns, D. M.; Theofanous, T. G.; and Houze, R. N., "Turbulent Characteristics of Two-Phase, Gas-Liquid Stratified Channel Flow" (1973). *Symposia on Turbulence in Liquids*. 116.
https://scholarsmine.mst.edu/sotil/116

TURBULENT CHARACTERISTICS OF TWO-PHASE, GAS-LIQUID STRATIFIED CHANNEL FLOW

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ABSTRACT

The turbulence characteristics of the bulk phases were studied in a stratified, two-dimensional, gas-liquid channel flow. Initial results are presented comparing mean velocity and turbulent intensity profiles with those obtained in a prior study at the same bulk phase Reynolds numbers. The results indicate that comparison of two realizations of stratified gas-liquid flow cannot be adequately done on the basis of bulk-phase Reynolds numbers. Comparisons must be based on some more fundamental relationships involving the gas-liquid interactions.

INTRODUCTION

Prediction of interphase (gas-liquid) transfer rates of momentum, mass and/or energy constitutes one of the important unsolved problems limiting design of practical engineering systems. The formulation and utilization of realistic transfer models require a knowledge of the fluid motions controlling the transfer processes. Models ignoring the nature of these motions (7) have proven unsuccessful. Other models (1), considering only gross flow properties, have met with meager success in very limited situations. More realistic transfer models proposed recently (3,6) acknowledge and take into account the intimiate role of the controlling turbulent fluid motions in the transfer process.

The turbulent motions in the immediate vicinity of the phase interface (interfacial region) are most important in determining the transfer rate. The structure (shape and motion) of the free phase boundary has effectively prevented an experimental or analytical study of these motions. The free boundary interacts with the motions in both phases and modifies them in a manner altogether different from that of a solid, impermeable phase boundary. There is some preliminary evidence (4,5) that the effects of the structured interface extend well into the regions of the phases away from the interface proper (bulk region). Quantification of these effects in the bulk region is the first step in approaching the more complex problem of studying the turbulent motions within the interfacial region. Knowledge of the characteristics of the bulk region flow fields is also required for the application of interphase transfer models recently developed by this group (8).

Stratified, two-dimensional flow is the simplest two-phase regime and has been investigated in only one previous study (4,5). This study observed an apparent anomalous behavior in the turbulent characteristics. Therefore, the present study was initiated to further investigate the turbulent flow characteristics of a stratified, two-dimensional, gas-liquid channel flow as a basis for a detailed analysis of the interfacial region.

EXPERIMENTAL FACILITY

The experimental investigation was conducted in a rectangular channel, 3 inches high, 24 feet long, with a 12:1 aspect ratio. As shown in Figure 1, air is drawn into the channel after passing through a filter/flow adaptor section (a). In the phase-joining

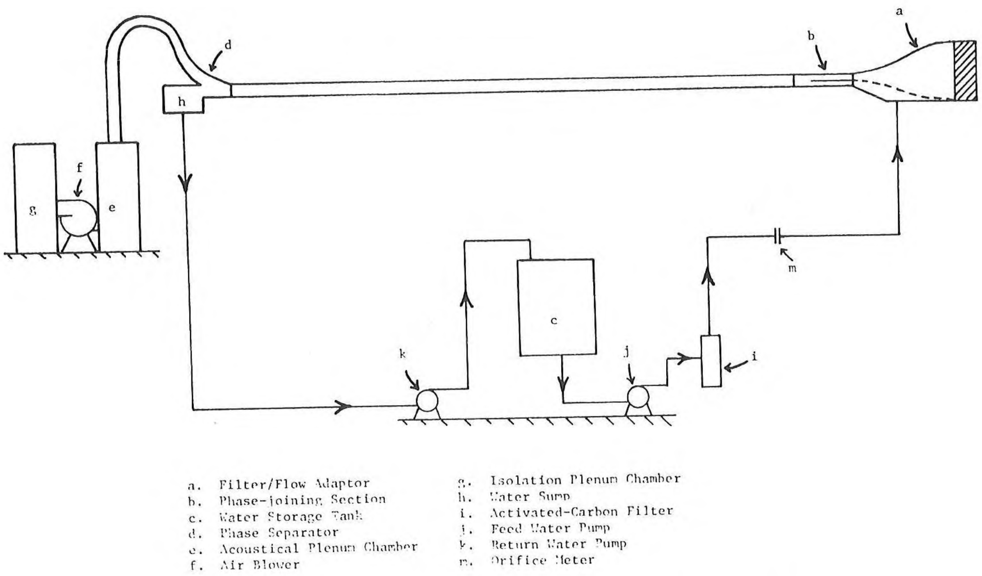


Figure 1. Experimental Flow Channel.

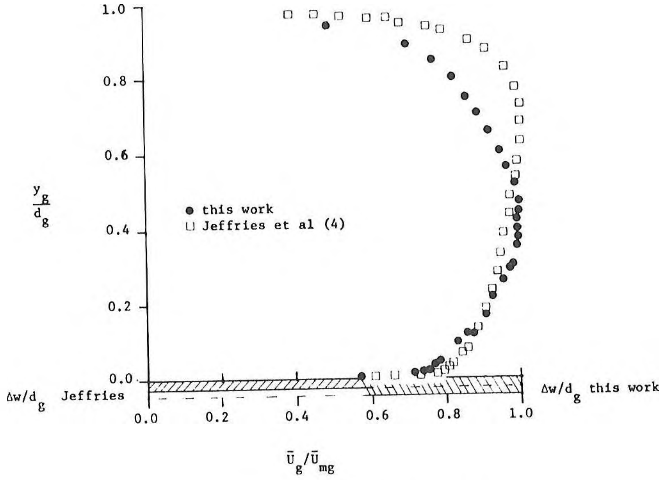


Figure 2. Mean Velocity Profiles in the Gas Phase (Re_g = 18,200)

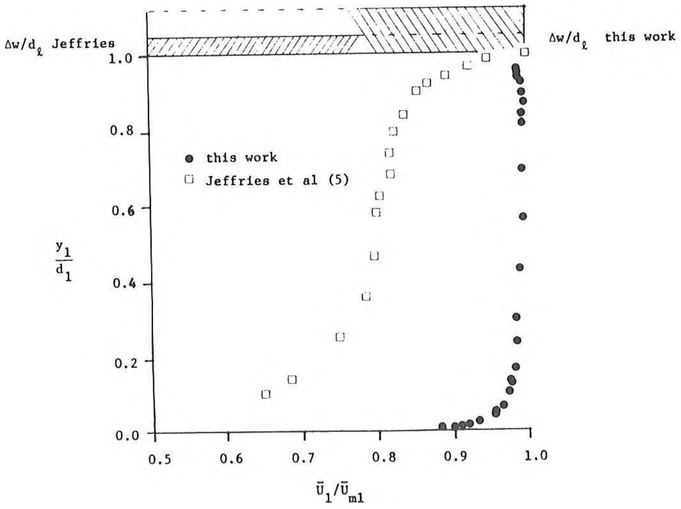


Figure 3. Mean Velocity Profiles in the Liquid Phase (Re_1 = 9,940)

section (b), the air joins with the water, which is pumped from a storage tank (c) to the bottom of the flow adaptor section. After passing through the channel, the air and water separate in the phase separator section (d). The air then flows through an acoustical plenum chamber (e), the blower (f) and an isolation plenum chamber (g) before exhausting to the atmosphere. The water flows into a sump (h) and is then returned by a pump to its storage tank. The air and water flow rates could each be independently controlled. All materials of construction were chosen to minimize contamination of the water, and filters impregnated with activated carbon (i) were employed to maintain low particulate and surfactant contaminant levels. The system has been shown to produce a stable, well-developed, two-dimensional flow configuration (2).

INSTRUMENTATION

All turbulence data were obtained with a linearized constant-temperature anemometry system (Thermo-Systems Model 1050)employing quartz-coated hot-film sensors. Single-sensor probes were utilized to obtain mean velocity and turbulent intensity distributions in both the air and water phases. The sensors were calibrated utilizing a stagnation pitot tube to measure the velocity at the point of maximum velocity. The location of the sensor elements within the channel was determined utilizing an automatic level and a reference mark on the channel side a known distance from the channel bottom. A Precision Instrument PI-6104 magnetic tape recorder was employed to acquire continuous recordings of the signals in the FM mode. Those signals of interest were then analyzed employing a General Radio Sound and Vibration Analyzer with a 1/10-octave window. Pressure measurements were obtained with a Meriam Micromanometer (Model 34FB2) which had a range of 10 inches of water and a resolution of 0.0005 inch of water.

RESULTS

Profiles of mean velocity and turbulent intensity in the flow direction were obtained for both phases in a single run with the gas and liquid Reynolds numbers chosen to match a representative set of conditions employed by Jeffries (4,5). The gas-phase Reynolds number (Re_g) was 18,200 and the liquid-phase Reynolds number (Re_l) was 9940. Representative energy spectral distributions of the liquid phase turbulent velocity fluctuations were obtained and are presented.

Figure 2 presents the gas phase mean velocity profile as a function of the distance from the top of the highest wave crests (y_g) following the procedure of Jeffries (4,5). Figure 3 presents the liquid phase mean velocity profile as a function of the distance from the bottom wall (y_l). Figures 4 and 5 present the relative turbulent intensities in the flow direction for both phases. In all the above figures, the corresponding data of Jeffries have been included for comparison. Figure 6 presents representative energy spectral distributions taken in the liquid phase both near the interface (y_l/d_l = 0.934) and near the solid bottom surface (y_l/d_l = 0.0278).

DISCUSSION OF RESULTS

Mean Velocity Profiles

The mean velocity profiles in the gas and liquid phases (Figures 2 and 3) are typical of profiles observed for low interfacial shear. This is evidenced by the extremely constant liquid velocity profile nearer the interface than the top channel wall. The data of Jeffries are more consistent with a high interfacial shear as evidenced by the shift of the gas-phase mean velocity maximum upward toward the top wall. In this study, the interfacial shear was approximately equal to the gas-phase shear on the top wall. In Jeffries' experiment, it was almost three times larger than the top wall shear (assuming a two-dimensional flow field). In the present study, the wave height (trough to crest) was 4.3% of the gas-phase thickness (0.092 inch) while in Jeffries' case it was 2.3% (0.024 inch). Even with this difference in the wave size, the interfacial structure affects the mean velocity profiles less in the present study than in Jeffries' study.

The low aspect ratio employed by Jeffries makes it very unlikely that his flow field was two-dimensional. Secondary motions, caused by wall effects, can drastically affect the flow properties. As will be seen in the next section, there is evidence that his data are inconsistent for this reason.

The inflection in the liquid-phase mean velocity profile near the interface is strongly suggestive of a developing flow field. Secondary motions within the liquid phase may be transporting low-momentum

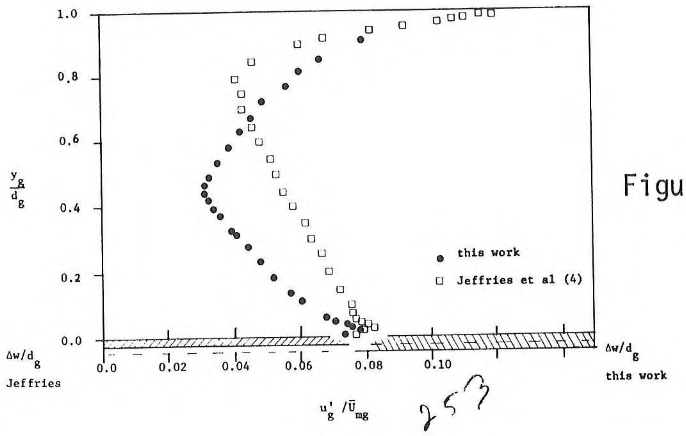
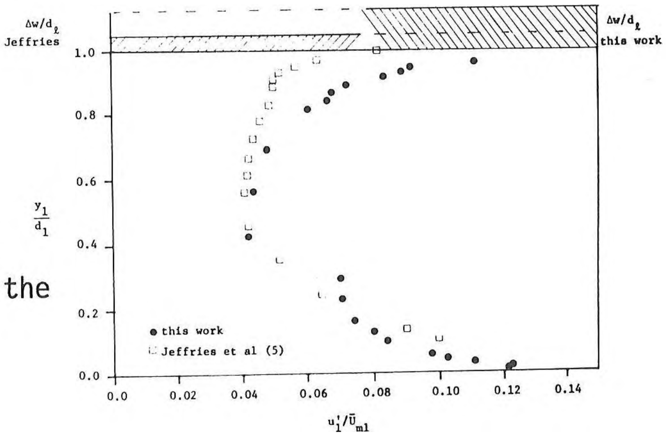


Figure 4. Turbulent Intensity Distributions in the Gas Phase (Re_g = 18,200)

Figure 5. Turbulent Intensity Distributions in the Liquid Phase (Re_l = 9,940)



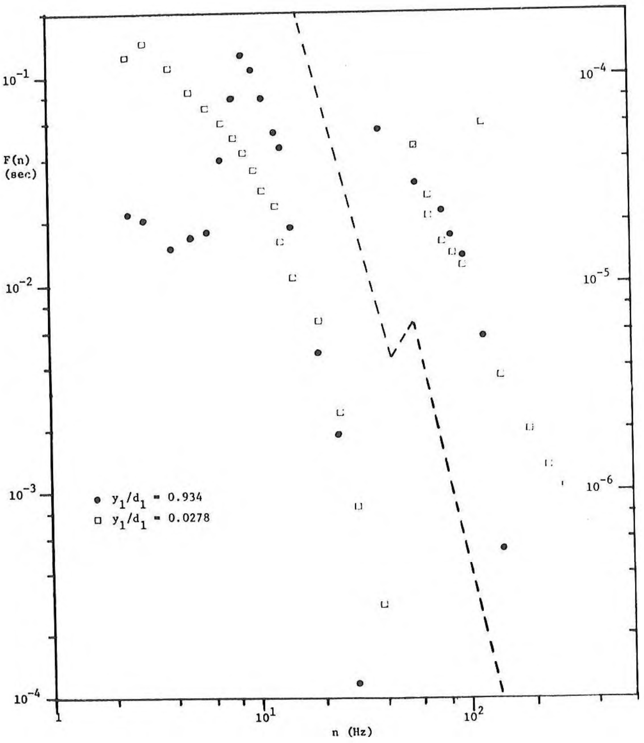


Figure 6. Normalized Energy Spectral Distribution in the Liquid Phase

fluid from the wall, into the region near the interface. This observation is being investigated further to determine if such a profile is reasonable for a fully-developed two-dimensional flow.

Turbulent Intensity Profiles

The turbulent intensity profiles, shown in Figures 4 and 5, are consistent in form with the observed mean velocity profiles. The gas-phase profile exhibits a minimum at exactly the same position as the maximum in the mean velocity profile. This is not true of Jeffries' results where the maximum in the mean velocity ($y_g/d_g \simeq 0.74$) is not the same as the minimum in the turbulent intensity profile ($y_g/d_g \simeq 0.8$). This difference is observed when the flow field is not two-dimensional, casting further doubt on the validity of Jeffries' results. Near the interface, the gas-phase intensity attains a local maximum and then decreases somewhat due to the damping effect of the liquid interface.

The liquid-phase intensity profile is consistent with the mean velocity profile except near the interface. Since the mean velocity is relatively constant within this region, there is no production of turbulent energy due to interaction of the turbulent shear stress and the mean velocity gradient, and the intensity should remain constant or decrease unless there is some other source of fluctuation energy. However, wave passage on the interface is known to induce unsteady motions within the liquid phase which decay with depth. If these motions are interpreted as turbulence, they will cause an apparent increase in the intensity as the interface is approached. Since these unsteady motions are sensed by the hot-film probe, the larger waves in the present study, as compared to Jeffries, would induce larger disturbances, thus contributing to the apparent increase in intensity as observed in Figure 5. Studies of the motions near the interface must take into account these wave-associated motions as well as the energy fed to the turbulent motions which is extracted from the gas phase by the waves.

Turbulent Energy Spectral Distributions

The spectral energy distributions in the liquid phase, presented in Figure 6, clearly exhibit the effect of wave passage. The distribution near the interface ($y_e/d_e = 0.934$) exhibits a large peak centered around 9 Hertz. The distribution near the channel bottom ($y_e/d_e = 0.0278$) does not exhibit any peak in this frequency range. The energy associated with this peak contributes approximately thirty per cent of the total turbulent energy at this location. The wave-induced motions are responsible for this concentration of energy and this is consistent with the increased intensity observed near the interface. Most of the turbulent energy is attributable to low frequencies with no significant energy found above 100 Hertz. No comparison of these spectral distributions can be made as Jeffries (4,5) presented no spectral data.

The shape of the spectral distributions is characteristic of low Reynolds number flows. Future studies must examine larger liquid Reynolds numbers to consider the case of a more well-developed turbulent energy cascade.

CONCLUSIONS

The comparisons presented in this paper with Jeffries' data should be viewed in the light that the flow characteristics of a stratified, two-dimensional gas-liquid flow field are extremely complex, and the basis for similarity between two different flow systems (or geometries) is not known. Comparisons between two different physical realizations of stratified gas-liquid flows probably cannot be effected solely on the basis of bulk-phase Reynolds numbers. The interfacial characteristics, which result from the gas-liquid interaction, must somehow be included in any meaningful comparison.

The data presented are the result of the initial phase of an extensive study of this two-phase flow configuration. Future work will include extensive measurements of intensities, shear stress, turbulent scales and spectral characteristics within the bulk phases. These measurements will provide a sound basis for the investigation of the motions very near the interface.

ACKNOWLEDGMENTS

This work is being supported by the National Science Foundation, Grant No. GK-36488. This support is gratefully acknowledged. Mr. L. K. Brumfield assisted in the design and construction of the equipment as well as the experimental phases, and his help is greatly appreciated.

SYMBOLS

d_g	distance from top of highest wave crest to top of channel, inches
d_l	distance from bottom of channel to bottom of lowest wave trough, inches
F(n)	normalized energy spectral distribution, sec
n	frequency, Hertz
Re_g	gas-phase Reynolds number based on hydraulic diameter and bulk velocity
Re_l	liquid-phase Reynolds number based on hydraulic diameter and bulk velocity
$\overline{U}_g$	gas-phase mean velocity, ft/sec
$\overline{U}_l$	liquid-phase mean velocity, ft/sec
$\overline{U}_{mg}$	maximum value of gas-phase mean velocity, ft/sec
$\overline{U}_{ml}$	maximum value of liquid-phase mean velocity, ft/sec
u'_g	gas-phase turbulent intensity, ft/sec
u'_l	liquid-phase turbulent intensity, ft/sec
y_g	distance measured from top of highest wave crest
y_l	distance measured from bottom of channel, inches
Δw	distance from bottom of lowest wave trough to top of highest wave crest, inches

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DISCUSSION

R. J. Hansen, Naval Research Lab: I have two comments. First, the liquid velocity measurements of Jeffreys show a very high shear stress near the liquid-gas interface. Do you have an explanation for this phenomenon? Second, the utility of your work could be enhanced by incorporating some of the recently developed techniques for characterizing the dynamic properties of a liquid-gas interface. Surfactants are typically present in systems of engineering interest and significantly affect dynamic interfacial behavior.

Houze: Your second point was well taken. Yes, we intend to look very closely at what's happening at the interface. That is a difficult problem and we realize this. This is the first step. Now I would have been tickled to death if our data would have agreed with Jeffrey's. I would have said great, we can forget about that and go on to more interesting problems, but we can't do that; we have to answer those questions.

Regarding your first point of high shear stress. Yes, I did a quick calculation, because this bothered us. We see this inflection and it seems reasonable that there should be an inflection, if you have a gas shear rate imposed on the interface. Of course, the wave structure seems to modify that because you get separation around the waves and it is a difficult problem. I did a quick calculation just to get some idea of the difference in velocity across the interface. You have to realize I am not talking about 0.001 inch in the liquid to the 0.001 of an inch in gas because I have this wavy region. Remember again we scale on the basis of a Reynolds number. So things are different. Ours is much bigger so our velocity is going to be much lower. The maximum velocity we measured in the liquid phase was about 0.68 feet per second. In the gas phase the minimum right next to the interface was 6.4 feet per second, so there is a factor of 10 there. With Jeffrey's data we made some estimations. In the liquid phase he had a maximum velocity of about 2 feet per second. Now the ratios are about the same, but the absolute magnitude is quite different. In addition his waves are so much smaller and if you consider just a viscous shear velocity gradient at the surface, with our waves we probably don't have that because of the separation. I really can't answer the question, because we haven't studied it enough to know. This is the point we are really looking into: If we made a mistake, should we have this large inflection there?

Shau-Zou Lu, Clarkson College: Have you observed the drifting problem with the water measurements?

Houze: We didn't encounter any significant drifting problems because this was only one run that we had done. I am sure there will be drifting problems, but we were able to reproduce our data over a period of six or seven hours very well, we didn't have any problems that way.

V. W. Goldschmidt, Purdue University: You calibrated before and after?

Houze: Yes, we checked the characteristics of the probe such as the bridge voltage out at zero flow and it had not changed appreciably. In fact, we used the probe several times taking it in and out of the water and it didn't change appreciably. Now admittedly, it is going to change and I know that and it has to be taken into account. We have tried to keep our water as cold as we could. We degassed the water with a slight vacuum on the storage tank and consequently we have not had any degassing problem or bubble formation on the probe and hot spots which can affect the calibration. We haven't gotten so much data that have had our probe drift enough to worry about.

Lu: I was just surprised because in our measurements, drifting is a problem and we use distilled water in the whole system. Did you filter your wave? It seems to me your energy spectra show about 30 percent of the total energy. I would assume that total intensity should be distinguished between the large waves and the turbulent intensity.

Houze: I agree, one point I guess I didn't make clear. What do you call these motions induced by wave passage, I don't call them turbulence because they are not caused by the standard mechanisms which generate turbulence. If you are going to talk about the controversy, are these motions important for the transfer process, I recognize the problem. Maybe you ought to take these out, extract them, remove them from consideration. But maybe they are important, we have to find this out. They are not turbulence.

B. M. Leadon, University of Florida: This is highly reminiscent of the air-sea interactions with which I am sure you must be familiar. But first there is a point I don't understand. Did you follow the wave surface with your probe?

Houze: No, we did not, it was stationary.

Leadon: Well, then the point that I would like to make is there are similar measurements on much larger waves, and it may be that you could scale their results down to compare with yours. This would have the effect of showing data much closer to the interface that you are interested in. I have no question but that there is a tremendous interaction and certainly momentum transport is much affected by the conditions in both the liquid and the gas. The data that has been taken at large scale using a wave follower does include turbulence measurements in both phases very close to the interface.

Houze: Yes, I am very familiar with that work, we have looked at that very closely, but my initial point was simply, let's find out what happens in the bulk.

G. K. Patterson, University of Missouri-Rolla: Just a short comment. You kept saying that there was a discrepancy between your data and the data of Jeffrey, indicating that possibly that one or the other had right data and the other had wrong data or data that wasn't quite as good. I was about to suggest that possibly both of them are right and there is some explanation having to do with this wave interaction and the lack of a strong connection between the two phases when you have the bigger waves.

Houze: The size of a two-phase flow has some very definite effects and you just can't scale things very well. We assumed that dynamic similarity would be preserved if we had the same Reynolds numbers and quite obviously it is not. Of course, the question is how much of the effect is three-dimensional probe problems? And how much of it is a scaling problem. We don't know.

T. J. Hanratty, University of Illinois: Why do you have larger amplitude waves than Jeffrey's?

Houze: That is very interesting, because if you will look at the relative heights of the waves as a function of the percentage of the total height of the channel, ours is smaller. Ours is only 2% of the he height of the gas phase. I am just saying, you try various ways of looking at it. Maybe one of the effects on the mean velocity profile of the gas was a relative roughness of the waves, giving a roughness type of effect. I think it is a geometric problem. Ours is a bigger system, and our waves are therefore larger. I don't have a good explanation beyond that.

A. Brandt, Johns Hopkins University: This morning we saw how inlet effects in a channel can be propagated to great distances downstream. I don't recall hearing you discuss the effects of the inlet profiles and the differences between the inlet conditions in your case and those of the study to which you are comparing your data. Would you also explain how the probe is positioned relative to the interface? Since you are interested in the transport processes you should be interested primarily in the region right near the interface.

Houze: Your first question was on the development of the flow - we did check this. We looked at the flow characteristics as a function of distance down the channel. The length of our channel in terms of hydraulic diameter is about 53. We were like 43 diameters downstream of the entrance. We went upstream about 10 feet or so and looked at our characteristics, particularly in single-phase flow and in some two-phase flow. We could see no significant differences over that length. Now there may be some effects which we haven't detected. We are making sure that the entrance characteristics are such that you don't have any disturbances. One comment that I could make is that in single-phase flow we did this to simply check ourselves and to see how good we were. We took some single-phase data and we were going to be very happy if it came even close to Laufer's, it fell on top of it. So we had some confidence that the channel itself, in terms of single phase flow, was giving us good results for air. Water is more difficult and we have that check to do yet. But I have a fair amount of confidence that it will agree. We arbitrarily picked one spike every twenty seconds and took that as the distance between the highest crest and lowest trough. Then we decided to try and find where the mean is so we said well, where should it be, if you put the probe in there somewhere and you look at the oscilloscope and it looks like about 50% of the time it is in and out, maybe that is the average. Then we took that reading on our micrometer then we said well let's see how that checks out with the average between and it was within 0.001 of an inch. So, of course I am not saying that should be the mean value, but we can detect where the interphase is, with a hot-film probe, fairly easily.

H. M. Nagib, Illinois Institute of Technology: What is the characteristic number here? You talk about the Reynolds number and the hydraulic diameter. I think we are talking about a flow that is developing from the entrance. I think that as long as it is still developing there are several characteristic numbers, just like a developing boundary layer. And I think that is how you want to compare your data. You said that yours was independent in the gas phase, was it independent in the liquid phase?

Houze: Yes, as far as we could tell, and as far as we could tell by looking at the wave, visually observing the waves. Visually observing the thickness of the liquid phase we allowed the liquid to just reach its own level.

Nagib: Was their data fully developed? In comparing the data I think you want to be a little bit more specific about the other characteristic numbers.

Houze: Certainly.

W. R. Penney, Monsanto Company: You propose to measure the fundamental characteristics of the turbulence and then use that to give us a design method for mass transfer?

Houze: We hope so.

Penney: And I presume that the characteristics of the turbulence will correlate with certain dimensionless parameters of the flow. Knowing the fundamental characteristics of the turbulence, have you thought about how you are going to develop this design method? If the turbulence characteristics correlate with the dimensionless parameters of the system, wouldn't it be just as easy to measure the mass transfer rates and go ahead and correlate those directly with the dimensionless parameters of the system?

Houze: Those are two very good questions. I didn't point this out but the group with which I work at Purdue has been working for at least three years on mass transfer models, and how they can be related to flow characteristics. And we have what we think or we hope are good models. And I think we have some data to show that they are. We have formulated these in terms of the turbulent characteristics but those aren't primary data. What you would like to do is give somebody a Reynolds number or a flow situation and say, what is my mass transfer coefficient? If I can get a measurement of the turbulent characteristics, then I can tell you what the mass transfer coefficient would be. I am going to stick my neck out and say within 10% over about two decades of mass transfer coefficient. What we have to do is validate this hypothesis of ours by looking at the mass transfer rates and simultaneously those characteristics of turbulence we think are important. Maybe we will find out that what we think is important is not and it is something else. The eventual step is to try to relate those characteristics to more gross flow parameters that are more easily obtained, so that we can then go directly to the mass transfer coefficient. The only comment that I had about your second question is that people have tried to do this, to correlate a mass transfer coefficient with the more gross characteristics of flow situation and haven't been successful.

C. A. Sleicher, University of Washington: If you are going to be interested in mass transfer rates then the appropriate dimensionless number of course is the Schmidt number, which typically for the mass transfer is over a thousand or more. And of course that means that you are going to have to get much closer to the interface than you have so far. That would be a problem.

Houze: That is exactly correct, and we recognize that problem. We haven't solved it, but we have recognized it. We don't know how close is close enough.

Leadon: The gas phase effect upon the water, I think, is a very important effect here, it causes the waves. When the waves are in action they tend to expose new surface, new molecules come to the surface of the water, so I think it is very bad to consider comparing this with a fixed surface. One of the primary variables must involve the wave height.

Houze: I showed my bias when I made the statement because my Ph.D. work was concerned with the flow of the gas over a simulated liquid interface which was impermeable and couldn't respond to the gas phase flow. So I got to thinking that way. You are right.