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GAS–LIQUID ANNULAR FLOW UNDER MICROGRAVITY CONDITIONS: A TEMPORAL LINEAR STABILITY STUDY

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Abstract—A temporal linear stability study was performed for a gas–liquid annular flow configuration under microgravity conditions. Data used to validate the modeling includes that generated by Texas A&M as well as all the other known data in two-phase flow under reduced gravity conditions. Following a discussion of theoretical considerations on the growth rates of different instabilities, it is shown that given the fluid properties, pipe diameter and phasic flow rates, one can predict with a high level of confidence the flow regime in the pipe. Acceptable confidence levels ($\sim$80%) are achieved when one differentiates between slug, slug–annular, and annular flow. Higher confidence levels ($\sim$90%) are found when one differentiates between slug and annular flow by merging the annular and slug–annular categories.

Key Words: gas–liquid two-phase flow, annular flow, microgravity conditions, linear stability analysis, experiment/theory

1. INTRODUCTION

Early space programs like Mercury and continuing up to the Space Shuttle have used gravity independent, single phase flow for thermal management purposes. It seems clear, however, that future spacecraft should take advantage of vapor–liquid, two phase flows. Indeed, this technology has the ability to carry more energy per unit mass than single phase flows while simultaneously operating at constant temperature. A two phase system also requires less pumping power per unit of thermal energy carried and has better heat transfer characteristics than a single phase system. These interesting features make two phase flows an ideal candidate for thermal management systems of future space projects.

In traditional two-phase flow studies, the flow regime refers to the physical location of the gas and the liquid. The flow configuration is important for engineering data correlation such as pressure drop, wall shear, heat and mass transfer. However it is somewhat subjective since it is mostly defined by the experimenter's eye; this results in an approximate definition. Thus there is a need for better discretizing instrumentation as evidenced by Segokushi & Takeishi (1989). In order to design a thermal management system, a chemical reactor or to predict an accident scenario in a nuclear power plant, one can usually estimate the phasic flow rates, but the missing information is the topological configuration of the phases. Hence, most investigations performed on the subject have tried to determine, through experimental and empirical means, when each flow regime configuration is likely to occur given the system parameters. This work will study the transition from an annular to slug flow configuration in a microgravity environment considering the fundamental fluid physics of the situation.

Since experimental observations of two-phase flows are limited for a reduced gravity environment (Best & Hill 1991, Chen *et al.* 1988; Colin 1990; Janicot 1988; Huckerby & Rezkallah 1992), an analytical framework was developed that would allow researchers to have some theoretical tools giving an insight into the transitions from annular to slug flow in cylindrical pipes. Georgevich (1991) studied a boundary-layer type, linear analysis of microgravity thick film, annular flow in order to predict the presence of dynamic and kinematic waves. Another implementation, (Carron 1992) of this effort was geared toward the evaluation of the temporal linear stability of the full

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Navier–Stokes equations for the annular flow configuration presented here. Carron's work is similar to the work performed by Preziosi *et al.* (1989) on water–oil core annular flows except that it is applied to a radically different region of fluid properties and velocities. The problem treated by Lin & Ibrahim (1990) of a liquid jet surrounded by a viscous gas is also similar but again lies in yet another region of the parameter space.

The primary purpose of the present work is to recognize the multifaceted combination of fluid properties used in different experiments and to allow a unifying criteria among experiments using different fluids.

2. EQUATIONS

We have studied the linear stability of an annular flow configuration (see figure 1) with respect to infinitesimal disturbances under microgravity conditions. The Navier–Stokes equations were linearized and solved using a pseudo-spectral method based on Chebyshev polynomials as in Preziosi *et al.* (1989).

In the two, separate phases one can write the continuity and the momentum equations for an incompressible, Newtonian fluid ($l = [1, 2]$, here 1 represents vapor and 2 liquid);

$$\operatorname{div} \mathbf{U} = 0 \qquad [1.1]$$

$$\rho_l \frac{\mathrm{D}\mathbf{U}}{\mathrm{D}t} = -\nabla P + \mu_l \Delta \mathbf{U} \qquad [1.2]$$

where ρ_l and μ_l represent the density and the viscosity of medium l. The boundary conditions imposed on the system are,

$$\mathbf{U} = 0 \text{ at } r = R_2 \qquad [1.3]$$

$$\mathbf{U} \text{ finite at } r = 0 \qquad [1.4]$$

the kinematic interface condition ($\mathbf{U} = (u, v, w)$),

$$u = R_t + wR_x + vR_\theta / R \quad \text{at } r = R_1 \qquad [1.5]$$

the continuity of the velocity and the normal stress of the interface.

$$[\mathbf{U}] = 0 \quad \text{at } r = R_1 \qquad [1.6]$$

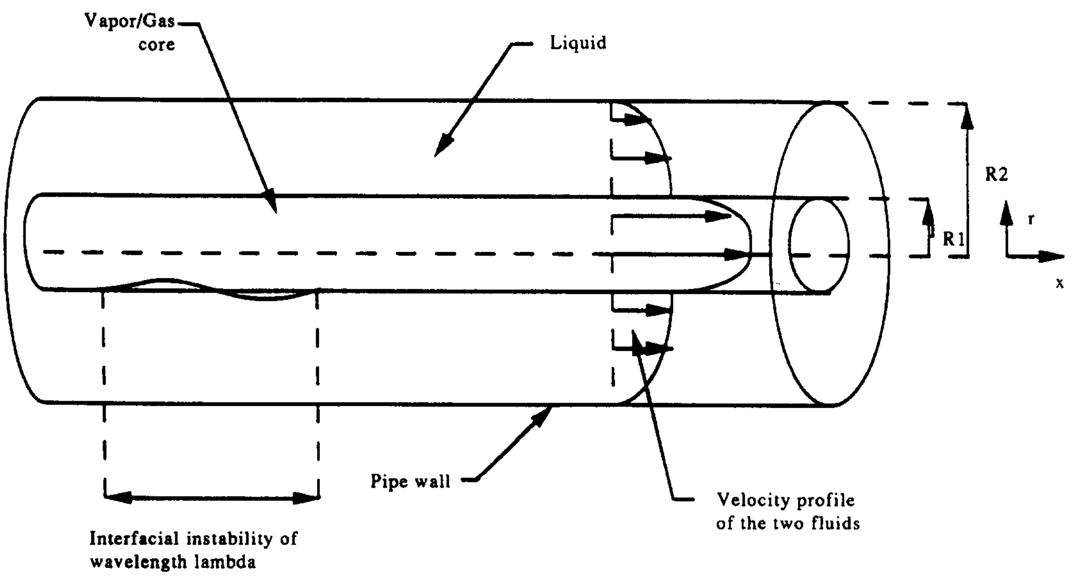

Figure 1. Perfect annular flow in a microgravity environment developing an instability at its gas–liquid interface.

$$-([P]+2\sigma \mathrm{H})\mathbf{n}+[\mu(\nabla.\mathbf{U}+\nabla.\mathbf{U}^T)].\mathbf{n}=0 \quad [1.7]$$

where for any quantity A, $[A]$ is equivalent to $A_1 - A_2$, σ is the surface tension, $2H$ is the principal radius of curvature at the interface, $\mathbf{n}$ is the unit vector normal to the concentric surface ($r = R_1$). Following Preziosi *et al.* (1989), the lengths are scaled with the radius R_1, velocity with maximum velocity W_0, the time with R_1/W_0, and the pressure with $\rho_i W_0^2$. The phase space is composed of six dimensionless parameters: two Reynolds numbers $\rho_i W_0 R_1/\mu_i$, a density ratio $\xi_i = (\rho_i/\rho_1)$, a viscosity ratio $m_i = \mu_i/\mu_i\ (=m)$, a dimensionless radius $a = R_1/R_2$ and a surface tension parameter $J = \sigma R_1/\rho_1 v_1^2$.

The system [1.1]–[1.7] can be thought of as operator $\mathbf{L}$ satisfying:

$$\mathbf{L}(\mathbf{B})=0 \quad [1.8]$$

where $\mathbf{B}$ represents a vector composed of the three coordinates of the velocity, the pressure and the interface location. In the framework of linear stability analysis, we are interested in solving [1.8] for a base state with a perturbation, $\mathbf{B} = \mathbf{B}_0 + \mathrm{B}$ with the condition that the base state also satisfies [1.8] i.e.:

$$\mathbf{L}(\mathbf{B}_0)=0 \quad [1.9]$$

with $\mathbf{B}_0 = (0, 0, W(r), P, R_1 = 1)$ representing the axisymmetric basic state from which one is studying the perturbation. After equating the axial pressure gradients in both fluids, the steady state solution for the axial velocity, $W(r)$, is found to be:

$$W_1(r) = 1 - mr^2/(a^2 + m - 1) \quad \text{for } 0 < r < 1,$$

$$W_2(r) = (a^2 - r^2)/(a^2 + m - 1) \quad \text{for } 1 < r < a,$$

$$P_1 - \xi_2 P_2 = J/\mathrm{Re}_1.$$

Developing $\mathbf{L}$ with respect to the infinitesimal perturbation $\mathrm{B} = (u, v, w, p, h)$ and expanding it around $\mathbf{B}_0$ in a Taylor series yields symbolically,

$$\mathbf{L}(\mathbf{B}) = \mathbf{L}(\mathbf{B}_0 + \mathrm{B}) = \mathbf{L}(\mathbf{B}_0) + \mathrm{B}\cdot\mathbf{L}^{(1)}(\mathbf{B}_0) + O(\mathrm{B}^2) = 0. \quad [1.10]$$

Our interest lies in the linear term of this expression. The zero order term vanishes due to equation [1.9]. Except for perturbation height h (which is not a function of r) all other terms of B are expanded in terms of a function of r and an exponential term,

$$\mathrm{B}(r, \theta, x, t) = \mathbf{B}' \exp(in\theta + i\alpha(x - Ct)) \quad [1.11]$$

with $\mathbf{B}' = (iu(r), v(r), w(r), p(r), \delta)$.

$\mathbf{B}'$ is evaluated in terms of Chebychev polynomials at specific and convenient collocation points. The discretization scheme yields a generalized eigenvalue problem of the type

$$A\mathbf{x} = CD\mathbf{x} \quad [1.12]$$

where A and D are N by N complex matrices and C and $\mathbf{x}$ are the eigenvalues and the eigenvector respectively. The study of temporal stability leads one to search for complex C's while varying the real wave numbers, α. An examination of the exponential expression in [1.11] shows the traditional result that an instability exists for C_i (the imaginary part of C) positive and that the growth rate of the instability is αC_i. The eigenvalue problem is solved using the IMSL library routine on a DEC-VAX 9000 and the NAG library routine when the computations were performed on the Texas A&M Cray YMP-116.

Benchmarking the solution was performed by checking against two sets of results. The first check batch was composed of the four papers published by Joseph's group (Bai *et al.* 1992; Chen *et al.* 1990; Hu & Joseph 1990; Preziosi *et al.* 1989) and one paper by Chen (Chen 1992). As shown by Carron (1992) our results were in excellent agreement with their computations. The second check batch was provided by Lin & Ibrahim (1990). While there was a mistake in their initial publication (see corrigendum Lin & Ibrahim 1992), their results are still not in agreement with the results computed by our code. However, considering that the codes were implemented totally separately, it is felt that the excellent agreement with the five different publications which are themselves backed up by experimental work, shows that a strong case is made for the accuracy of the code developed in our work.

The computations were repeated with different numbers of collocation points in order to eliminate spurious eigenvalues. The spurious eigenvalues are thought to be the result of the discretization and the numerical scheme. The computation of the eigenvalue and the relative error are two different things. The convergence criterion for the calculation of an eigenvalue was selected by the NAG subroutine. We defined relative error as the percent difference between converged eigenvalues in successive spatial approximations. An inaccuracy of 8% in the relative error happens in few cases and they generally occur when computing growth rates for small wavelengths (or high critical wavenumbers, i.e. above 15). Most of the time, the relative error is about 1–3%. There is a trade-off between the present state-of-the-art computing resources and these survey calculations. The 1–3% error was felt to be accurate enough for the computations we did in comparison with the accuracy of the experimental data. Twenty-three growth rates were computed for each experimental data point (a data point consists of a set of fluid properties, flow rates, pipe diameter and flow regime identification). The wave numbers covered values from 0 to 22 with a denser grouping in the long wavelength limit ($\alpha < 1$). A total of 80 h of Cray YMP-116 time was needed to generate the results presented here.

3. EXPERIMENTS. DESCRIPTION OF THE FACILITIES

In this article we look at most of the experimental work which has been carried out on adiabatic, microgravity two-phase flow. The experimental database includes:

—Experiments conducted by other researchers, these include the work of Fabre & Colin (Colin 1990; Colin *et al.* 1991) in France, Huckerby & Rezkallah (1992) in Canada and Dukler (Janicot 1988) at the University of Houston, Texas.

—Experiments performed by or with the help of our group, namely Lee (1987), Reinarts (1992) and Best & Hill (1991), Crowley & Sam (1991) and a previously unpublished precursor experiment documented by Carron (1992).

These experiments are listed in table 1 with flow rates and possible sources of error. The selection was made of these experiments positively identifying the different flow regimes. Other criteria included wetting liquid–wall experiments, a long test section allowing flow development and an average of at least 5 s of microgravity. Most of the flow rate information of these experiments were summarized by Reinarts in his dissertation (Reinarts 1992).

In order to reproduce weightless conditions, investigations in our group were performed aboard the National Aeronautics and Space Administration's (NASA) KC-135 reduced gravity aircraft. The experimental plane is operated by the Reduced Gravity Office at the Johnson Space Center, Houston, Texas. The aircraft flies parabolic trajectories in an altitude envelope ranging from 24,000 to 37,000 ft, which allows free-fall periods of about 20–30 s. The gravity level during this period remains in the range of $-0.1g$ to $+0.1g$ (Marsden & Best 1993). High quality gravity level ranging from $-0.05g$ to $+0.05g$ can be obtained for about 10–20 s. There are a fair number of parabolas that are not of high quality depending on the pilot, the weather and other uncontrolled behaviors.

The purpose of most of the ITP's experiments in the KC-135 was not to respond to a phenomenological study of the gas–liquid interface but to a more urgent need for engineering data such as the evaluation of Space Station hardware, the stability of evaporation and condensation loops, flow regime evaluation and pressure drop measurements. While those experiments were relatively successful in assessing a basic understanding of those behaviors, the instrumentation has not yet reached the sophistication achieved in the very controlled environment of the typical laboratory such as the one presented in Bai *et al.* (1992). The KC-135 environment remains far from congenial for instrumentation (Marsden & Best 1993) and inflexible when compared to most ground facilities. These unusual constraints make the learning process very unique and demanding for the experimenters. Other planes were used by other experimenters, namely a Lear jet operated by NASA Lewis Research Center and a Caravelle operated by CNES/DGA in France.

Table 1. Retrospective of microgravity experiments

	Fluid	Number of points	Determination of flow rates	Probable source of errors
Precursor experiment 1986 (Carron 1992)	Water–air	13	—Imposed by high precision syringe pumps —One pump for each fluid	—Gravity
Lee, Kashnik & Best (Lee 1987)	Water–air	7	—Measurement using two pressure transducers Low accuracy for the gas flow rate	—Gravity —Fore–aft location of package, stagnation phenomena
Chen & Downing (Cheng *et al.* 1988)	R-114	9	—Total mass flow rate computed from energy balance	—Gravity —Operating at 64°C in plane = loss at ambient temp. —Swirl flow evaporator coupled with G-transients
Hill & Best (1991)	R-12	2*19	—Mass flow rates evaluated at the all-liquid feedline and at the all-vapor feedline	—Gravity —Defective vapor sensor
Colin & Fabre (Colin 1990)	Water–air	133	—Mass flow rates evaluated separately on each line before mixing	—Gravity
Duckler & Janicot (Janicot 1988)	Water–air	20	—Mass flow rates evaluated separately on each line before mixing	—Gravity
Huckerby & Rezkallah (1992)	Water–air	49	—Mass flow rates evaluated separately on each line before mixing	—Gravity —Others? (see Reinarts 1992)
Sam & Crowley (1991)	R-11	9	—Total mass flow rate evaluated from energy balance	—Gravity —Reorientation of the mixture in the evaporator during G transients
Reinarts, Best *et al.* (Reinarts 1992)	R-12	97	—Mass flow rates evaluated separately on each line before mixing	—Gravity —At very low flow rates: high inaccuracies in vapor flow rates

4. RESULTS AND DISCUSSIONS

Given the flow rates, properties and geometry, a computation of the growth rate curve for each of the data points was performed. The total numbers of experimental points is 374. Figure 2 is a plot of growth rate versus wave number. It shows two distinct growth rate curves obtained for two different experimental occurrences. Curve 1 results from, typically, a slug flow, whereas the second curve results from an annular flow. It would be tedious to study all 374 of those figures individually. Hence, one is looking for ways to characterize those curves. Carron (Carron 1992, chapter 3) showed that experiments controlled by a capillary instability discovered by Rayleigh (Rayleigh 1879) and refined by others (Chandrasekhar 1961) for liquid jets were seen to result in a slug flow configuration. He also showed that there was no quantitative agreement between the most unstable wavelength computed from theory and the length of the bubbles in experiments. When, for a particular set of flow rates, the growth rate curve is found to be positive over a wide range of wavenumbers, one should not expect to find the unique and circumstantial agreement obtained for liquid jets. On the contrary, one should be drawn to the conclusion that the perturbed base state is always unstable and will not be seen experimentally. Moreover, the viscosity ratio of our gas/liquid experiments is known to produce an unstable core annular configuration (Preziosi *et al.* 1989) so that traditional elements of investigation of the linear stability theory and other related non-linear theory are not applicable.

Chen & Joseph (1991), however, judiciously point out that the linear theory might break down very rapidly at small wavelengths (large wavenumber) because of the interaction of small interfacial terms among themselves due to the convection terms. The interaction of the disturbance terms with each other leads to exponential terms with twice the original wavenumbers, this cascade induced by the convection term produces smaller wavelengths, emphasizing an energy transfer to smaller length scales. This process follows the direction of Kolmogorov theory on energy transfer in turbulence where a constant supply of energy is driven from the large scales to the smaller scales

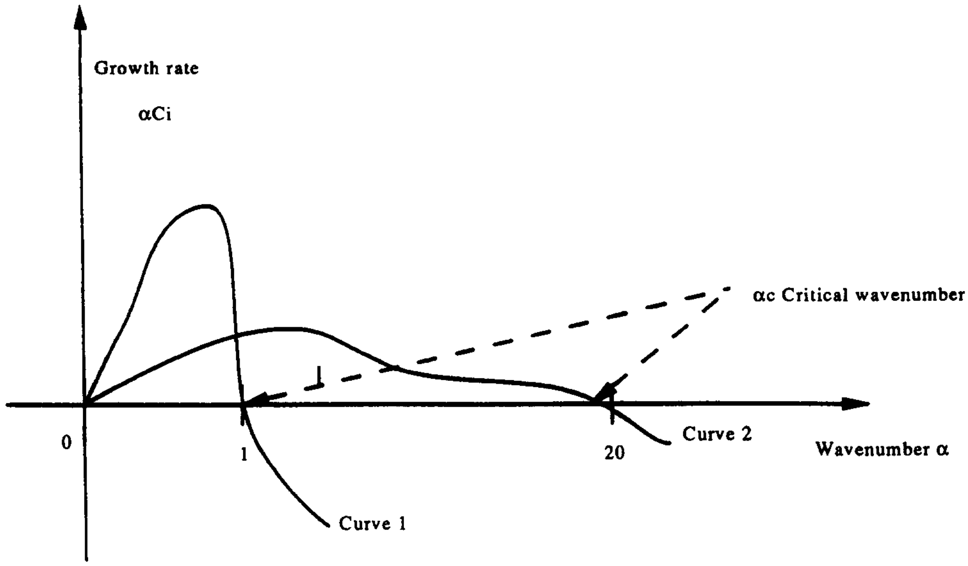

Figure 2. Sample of different growth rate curve for two different situations. Curve 1 represents typically a slug flow configuration and curve 2 represents typically an annular flow configuration.

(Kolmogorov 1941). In that regard, if one pictures a perfect, concentric flow being perturbed by all wavenumbers which appear to be positive in the growth rate curve, one is led to abandon the traditional interpretation of physical result linked solely to the highest growth rate and study instead how the different structures with wavenumbers corresponding to positive growth rates produce physical results. One has to think of the initial conditions as filtering those unstable structures. This argument follows the approach of Farge (Farge 1992) on turbulence and energy transfer, where she says 'Perhaps universality (universal behavior of turbulence) isn't where we think it is; perhaps we should, instead, search for it, in the shape of the coherent structures and in their elementary interactions'. In our case these coherent structures are the interfacial waves while the linear theory should give us the probability to potentially find certain types of structures in the flow.

Let us name the critical wavenumber, α_c, the wavenumber for which the growth rate equals zero as shown in figure 2. If $\alpha_c < 1$ (long wavelengths), then one may expect a capillary instability to be dominant and therefore observe experimentally a slug or a bubbly flow. If $\alpha_c \gg 1$ then one may expect a competition between the capillary instability and smaller wavelengths leading up to a slug, an annular or a transition flow between the two.

Following this argument, it is proposed that the critical wavenumber α_c can be a reliable parameter indicating when the flow is annular, slug/annular or slug and bubbly. Since we are interested in the transition from annular flow to other flows we will categorize slug and bubbly flow in the same category.

A first look at five experiments (considered the most reliable) and set the two values of α_c delimiting the region of transition for the three previously mentioned flow configurations. Those experiments were considered more reliable in that the gas and the liquid flow rates were separately monitored. Those experiments include: our precursor experiment (Carron 1992), the air–water experiments of Fabre and Colin (Colin 1990), Dukler and his group (Janicot 1988), Huckerby & Rezkallah (1992) and R-12 experiment (Reinarts 1992).

The tables now presented are constructed in the following way; for each experimental condition, the row indicates in which category the flow was recognized by the experimenter and the column indicates in which interval the computed critical wavenumber of the experimental point is located. Therefore, for a successful prediction based on the critical wavenumber, one needs ideally to have 100% marks in the diagonal of the tables. The non-diagonal terms represent the mismatch between prediction and actual occurrence. Further, experimenters tend to choose test conditions based on their interest at the time rather than spread test conditions uniformly over the possible test space.

Table 2. Comparison of prediction with the most reliable experiments

Computation Occurrence	Critical wavenumber	6.41	9.92	Total number of points
Slug	96.67%	2.83%	0.47%	212
Slug–annular	10.33%	86.2%	3.45%	29
Annular	1.43%	12.86%	85.71%	70

Thus, a particular researcher may create test conditions which are all bubbly or all annular flow conditions. The results of this is that the percent "accuracy" which is reported in the following tables is not a true statistical sampling and should not be interpreted as a trend indicator.

Table 2 shows that by taking $\alpha_{c1} = 6.41$ and $\alpha_{c2} = 9.92$ it is possible to discriminate among three different flow regions: slug, slug–annular and annular flow in at least 85% of the cases. The percentage of successful identification increases when one considers the slug–annular region to be part of the annular region since the experimenter's eye and interpretation may differ from one group to another! Table 3 shows, in that case, that the predictive capabilities based on α_c improve to nearly 96% on 311 points. Table 2 can be further improved by explaining the occurrence of the high non-diagonal terms. At first glance, one can see that there is a disproportionate amount of data for slug flow compared with annular flow. This is mainly due to Fabre and Colin's database (Colin 1990) being oriented to slug and bubbly flow points (133 points). They constitute nearly one-third of the database.

One out of their 133 points is, based on our calculations, in the wrong place; i.e. our prediction is that it is in the slug–annular region (2.83%). Colin in her dissertation (Colin 1990) qualifies this point as intermittent, it may be that flow is not sufficiently developed to observe an annular flow. Four points from Rezkallah are also in this predicted slug–annular region while they are identified as slug flow. Reinarts (1992) shows that those some points are inconsistent with the rest of their database.

Three of our points (10.33%) are identified in the slug–annular region while the prediction is for slug flow. At least two of those points had a potential 50% error in the vapor flow rate (Reinarts 1992). The last point is close to the boundary between the two regions.

Seven of our points (12.86%) were experimentally identified as annular flow while their prediction lies in the slug–annular region. Several explanations can be offered to understand this offset. As noted before, the experimenter's eye is probably not the most reliable flow regime identification tool. Furthermore, for each of our tests, high speed digital imagery was used. Each of the shot takes between 1 and 1.5 s of the flow at 1000 frames/s. It is possible to imagine that this time period was not long enough to see long capillary waves especially in this region where they are supposed to be infrequent because of the proximity to the so-called annular flow region.

Finally, tables 4 and 5 show the results of all the computations for all the experiments listed above (including the less accurate ones). While the quality of the prediction is degraded, we still have a confidence level of about 93% when one wants to discretize annular from slug flow only. Even though that is not 100%, it was noted during the computations of those results that except for the database of Rezkallah (4 points) and Lee 1988 (3 points), each experiment is self-consistent in that the higher the α_c the better the chance to find, experimentally, an annular flow configuration.

Table 3. Reduced comparison with the most reliable experiments

Computation Occurrence	Critical wavenumber 6.41		Total number of points
Slug	96.67%	3.33%	212
Slug–annular and annular	4.04%	95.96%	99

Table 4. Distribution of experimental flow regimes vs their critical wavenumber

Computation / Occurrence	Critical wavenumber	6.41	9.92	Total number of points
Slug	93.75%	5.8%	0.44%	224
Slug–annular	18.18%	75.75%	6.06%	33
Annular	2.6%	23.93%	73.50%	117

Table 5. Comparison between experimental flow regimes vs their critical wavenumber for the complete set of microgravity experiments

Computation / Occurrence	Critical wavenumber	6.41	Total number of points
Slug	93.75%	6.25%	224
Slug–annular and annular	6.0%	94.0%	150

5. CONCLUSION

In our computations we have not considered several elements limiting the linear stability theory. It is obvious that entrance effect should be taken into account as well as a better understanding of the definition of equilibrium (i.e. equilibrium state of the non-linear evolution of the flow). However, it is striking that the linear stability theory of core-annular flows provides a single parameter that predicts the highly non-linear state of the flow with a confidence of up to 95% in differentiating slug flow from other regimes, for different fluids of radically different properties such as air–water and Freon 11, 12 and 114.

We have also shown that by taking the best data available on our current knowledge and estimation of the KC-135 facility (or other reduced gravity aircraft), it was possible to predict the flow regime with an accuracy of at least 85% in those experiments whether it was slug or bubbly, slug–annular and annular flow. It is a surprise to find out that the temporal linear stability analysis gives such a good picture of the hydrodynamics of such chaotic flows.

Future work includes an optimization to assess more accurately the critical wave numbers for the transition from slug to slug–annular and annular flow. It also should include an investigation of the initial conditions of the flow encountered at the point of mixing for the two fluids and an extension of this work to annular gas–liquid flow under gravity conditions and possible refinement of the criteria derived in this publication, i.e. relate α_c more directly to the physics of the flow.

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REFERENCES

Bai, R., Chen, K-P. & Joseph, D. D. 1992 Lubricated pipelining: stability of core annular flow part V: experiment and comparison with theory. *J. Fluid Mech.* **240**, 97–132.

Best, F. R. & Hill, W. 1991 Microgravity two-phase flow experiment and test results, presented at the *21st Int. Conf. on Environmental Systems*, San Francisco, Calif., 15–18 July.

Carron, I. 1992 Temporal and spatial analysis of annular flow under microgravity conditions, M.S. Thesis, Texas A&M Univ., College station, Tex. (unpublished).

CHANDRASEKHAR, S. 1961 *Hydrodynamics and Hydromagnetic Stability*. Dover, New York.

CHEN, I.-Y., DOWNING, R. S., PARISH, R. & KESHOCK, E. 1988 Reduced gravity flight experiment: observed flow regimes and pressure drops of vapor and liquid flow in adiabatic piping. *25th National Heat Transfer Conf.*, Houston, Tex.

CHEN, K.-P. 1992 Short wave instability of core-annular flow. *Phys. Fluids* **A4,** 186–188.

CHEN, K.-P., BAI, R. & JOSEPH, D. D. 1990 Lubricated pipelining, part 3: stability of core annular flow in vertical pipes, *J. Fluid Mech.* **214,** 251–186.

CHEN, K.-P. & JOSEPH, D. D. 1991 Long wave and lubrication theories for core annular flow. *Phys. Fluids* **A3,** 2672–2675.

COLIN, C. 1990 Ecoulements diphasiques a bulles et a poches en micropesanteur. Ph.D. Dissertation, Institut National Polytechnique de Toulouse, Toulouse, France.

COLIN, C., FABRE, J. & DUKLER, A. E. 1991 Gas–liquid flow at microgravity conditions. I. Dispersed bubble and slug flow. *Int. J. Multiphase Flow* **17,** 4, 533–544.

CROWLEY, C. J. & SAM, R. G. 1991 Microgravity experiments with a simple two-phase thermal system, PL-TR-91-1059, Philips Lab., Kirtland Air Force Base, NM 87117-6008.

FARGE, M. 1992 The continuous wavelet transform of two-dimensional turbulent flows. In *Wavelets and their Applications* (Edited by RUSKAI, M. B., BARTLETT & JONES), pp. 275–302.

GEORGEVICH, V. 1991 Analytical modeling and experimental investigation of interfacial waves in annular microgravity two-phase flow, Ph.D. dissertation, Texas A&M Univ., College Station Tex.

HU, H. & JOSEPH, D. D. 1990 Lubricated pipelining: stability of core annular flow, Part 2. *J. Fluid Mech.* **205,** 359–396.

HUCKERBY, C. S. & REZKALLAH, K. S. 1992 Flow pattern observations in two-phase gas–liquid flow in a straight tube under normal and microgravity conditions. *28th National Heat Transfer Conf.*, San Diego, Calif.

JANICOT, A. J. P. 1988 Experiment and theoretical studies of gas–liquid two-phase flow at reduced gravity conditions. M.S. Thesis, University of Houston, Houston, Tex. (unpublished).

KOLMOGOROV, A. M. 1941 Dissipation of energy in the locally isotropic turbulence. *C.R. Acad. Sci. URSS* **32,** 16–18.

LEE, D. 1987 Thermohydraulic and flow regime analysis for condensing two-phase flow in a microgravity environment. Ph.D. Dissertation, Texas A&M Univ. College Station, Tex.

LIN, S. P. & IBRAHIM, E. A. 1990 Instability of a viscous liquid jet surrounded by a viscous gas in a vertical pipe. *J. Fluid Mech.* **218,** 641–658.

LIN, S. P. & IBRAHIM, E. A. 1992 Corrigendum. Instability of a viscous liquid jet surrounded by a viscous gas in a vertical pipe. *J. Fluid Mech.* **240,** 685–686.

LORD RAYLEIGH 1879 On the instability of jets. *Proc. Lond. Math. Soc.* **10,** 4–13.

MARSDEN, K. & BEST, F. R. 1993 Vertical acceleration conditions in the NASA KC-135. *Int. Conf. on Environmental Systems.* 12–15 July, Colorado Springs, Col.

PREZIOSI, L., CHEN, K.-P. & JOSEPH, D. D. 1989 Lubricated pipelining: stability of core annular flow. *J. Fluid Mechanics* **201,** 323–356.

REINARTS, T. R. 1992 Adiabatic two-phase flow regime and modeling for zero and reduced (horizontal flow) accelerated fields. Ph.D. Dissertation, Texas A&M Univ., College Station, Tex.

SEGOKUSHI, K. & TAKEISHI, M. 1989 Interfacial structures in upward wave flow and annular flow regimes. *Int. J. Multiphase Flow* **15,** 295–305.