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TWO-PHASE POTENTIAL FLOW

Progress Report

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G. B. Wallis

**Thayer School of Engineering
Dartmouth College
Hanover, NH 03755-8000**

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Abstract

Progress towards developing a mature science of *two-phase potential flow* is reported in three areas:

- Fundamental theorems concerning the properties of dispersed systems
- Theoretical derivation of these properties
- Experimental confirmation

Applications to regular arrays of spheres or spheres in tubes is nearing completion.

New work is reported on flows with unknown interface geometry, as in gas-liquid flows. The interface shape is predicted as part of the solution.

1. Introduction

We have continued to pursue the objective of developing a basic science of two-phase flow. The systems chosen for study were either simple enough to allow exact solutions to be developed, or sufficiently well-defined to allow direct determination of macroscopic properties.

The main areas of effort have been the same as those itemized in our July 1992 progress report:

- Derivation of Averaged Continuum Equations
- Applications to Two-Phase Continua
- Exact and Approximate Solutions
- Theory and Experiments for Finite Systems

This work has led to the completion of three theses, several journal articles and others in preparation.

The major advances in the past year have been:

- Specific results for rectangular arrays,
- Prediction of new properties such as compressibility or particle stress,
- A start on non-linear aspects of sphere interactions
- Results for gas-liquid flows in which the geometry of the interface is part of the solution

2. Theses Completed

Three students who are graduating in June 1993 received support from this contract.

X. Cai Ph.D. Thesis title, "Inertial Coupling in Two-Phase Flow: A Few Test Cases and their Impacts on Two-Fluid Modeling."

This thesis contains some general theory of inertial coupling exemplified by more complete solutions to the classical sphere-in-sphere problem, new solutions for rows of discs or spheres on the axes of tubes (1), predictions for assemblies of spheres using the method of images (2) and close comparisons between the latter two for the case of rectangular arrays (3). Various definitions of the *added mass coefficient* are given and shown to be compatible. The role of *external impedance* in a fluid circuit, of which the assembly and its surrounding fluid forms a part, is examined.

Experimental results of the oscillation of numerous arrays of spheres in tubes substantially agree with these theoretical predictions without the need for empirical coefficients (3).

C. Luo Ph.D. Thesis title, "Inertial Coupling of Spherical Particles Dispersed in a Two-Phase Potential Flow."

This is a basic study of inertial coupling, providing rigorous, self-consistent derivations of the *resistivity tensor* and *added mass tensor* as *intrinsic properties* of a dispersion. The coupling with external constraints is examined. Specific results are obtained for rectangular arrays of spheres, including an approximate formula in terms of simple functions.

These results influenced the paper prepared for the London workshop in June 1992. Dr. Luo has written a draft paper for the Journal of Fluid Mechanics.

O. Mikhailov, M.S. Thesis title, "Numerical Solutions for Several Free-Surface Two-Phase Flow Problems."

Numerical algorithms were first used to solve several classical problems:

- Motion of a long "slug flow" bubble in viscous fluid,
- Motion of a long "slug flow" bubble in an inviscid fluid,
- The effects of surface tension on the above.

The results were more complete and less equivocal than those from previous studies. Convergence depended on specific values of dimensionless groups, providing predictions of bubble rise velocity in agreement with data. The shape of the interface was obtained as part of the solution.

New solutions were obtained for the flow of a jet detaching from the wall of a vertical tube, or for the inverse problem of liquid held up in a vertical tube by a countercurrent gas flow. Three distinct solutions were obtained, with contact angles of 0° , 60° and 90° .

Solutions were also obtained for the countercurrent flow of both gas and liquid into the top of a vertical tube. The resulting steady-state surface profiles did not lead to a "flooding" limit. Experiments revealed that flooding occurred as a result of the instability of the interface.

FURTHER WORK

The theses of Cai and Luo are part of our effort to establish a solid basis of understanding of two-phase potential flow.

In addition, their results have been used to obtain the stresses in a rectangular particle assembly. These may be interpreted as a *compressibility* or *particle stress* and, in the case of a cubical array, are consistent with predictions of Sangani and Didwania (4).

Moreover, new theorems have been derived for the polarization of a sphere in an array as well as methods for deriving *intrinsic* properties that do not depend on the macroscopic geometry and may be computed without convergence problems.

A new Ph.D. student, Oleg Dubitsky, has been studying the interaction between pairs of spheres in potential flow and the implications this may have for the properties of ensembles. The first order motion is independent, as in the kinetic theory of gases. However, the interaction is non-linear, leading for example to generation of a multiplicity of higher frequencies when one sphere is oscillated sinusoidally. Of particular interest to us is how the orderly motion of an assembly may be converted to random motion (or vice versa?) as a result of interactions.

PUBLICATIONS

Since our previous progress report the following articles have appeared in the peer-reviewed literature:

Sergeev, Y.A. and G.B. Wallis, "Concentration/Density Shocks in an Inertially-Coupled Two-Phase Dispersion," *Int. J. Multiphase Flow*, 18(5), 691-704, 1992.

Wallis, G.B., "Macroscopic Properties of a Two-Phase Potential Dispersion Composed of Identical Unit Cells," *Int. J. Multiphase Flow*, 18(6), 989-1017, 1992.

Wallis, G.B., X. Cai and C. Luo, "Inertial Coupling in Dispersed Potential Flow - Use of the Method of Images," *Chemical Engineering Communications*, 118, 141-162, 1992

Cai, X. and G.B. Wallis, "An Experimental Study of the Added Mass Coefficient: Rows and Arrays of Spheres Oscillating Along the Axes of Tubes," *Physics of Fluids A*, 5(7), 1614-1629, 1993

The following articles have been accepted for publication and are in press:

Wallis, G.B., "The Concept of Polarization in Dispersed Two-Phase Potential Flow," *Nuclear Engineering and Design*, 1993

Wallis, G.B., S.P. Harvey and R. DiFelice "Decompression Waves in Fluidized Beds," *Int. J. Multiphase Flow*, 1993

References

1. Cai, X. and G.B. Wallis "Flow Around a Row of Spheres in a Circular Tube," *Physics of Fluids A*, 4(5), 904-912, 1992.
2. Wallis, G.B., X. Cai and C. Luo, "Inertial Coupling in Dispersed Potential Flow - Use of the Method of Images," *Chem. Eng. Comm.*, 118, 141-162, 1992.
3. Cai, X. and G.B. Wallis, "The Added Mass Coefficient for Rows and Arrays of Spheres Oscillating Along the Axes of Tubes," *Physics of Fluids*, 1993
4. Sangani, A.S. and A.K. Didwania, "Dispersed-phase Stress Tensor in Flows of Bubbly Liquids at large Reynolds Numbers," *J. Fluid Mech.*, 248, 27-54, 1993

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