TWO-FLUID MODEL AND INTERFACIAL AREA TRANSPORT IN MICROGRAVITY CONDITION

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The objective of the present study is to develop a two-fluid model formulation with interfacial area transport equation applicable for microgravity conditions. The new model is expected to make a leapfrog improvement by furnishing the constitutive relations for the interfacial interaction terms with the interfacial area transport equation, which can dynamically model the changes of the interfacial structures. In the first year of this three-year project supported by the U.S. NASA, Office of Biological and Physics Research, the primary focus is to design and construct a ground-based, microgravity two-phase flow simulation facility, in which two immiscible fluids with close density will be used.

In predicting the two-phase flow behaviors in any two-phase flow system, the interfacial transfer terms are among the most essential factors in the modeling. These interfacial transfer terms in a two-fluid model specify the rate of phase change, momentum exchange, and energy transfer at the interface between the two phases. For the two-phase flow under the microgravity condition, the stability of the fluid particle interface and the interfacial structures are quite different from those under normal gravity condition. The flow structure may not reach an equilibrium condition and the two fluids may be loosely coupled such that the inertia terms of each fluid should be considered separately by use of the two-fluid model. Previous studies indicated that, unless phase-interaction terms are accurately modeled in the two-fluid model, the complex modeling does not necessarily warrant an accurate solution.

Traditionally, the interfacial area concentration, one of the parameters characterizing the interfacial structure, is specified by empirical correlations that are based on the two-phase flow regimes and regime transition criteria. In view of this, the focus of many studies for the microgravity two-phase flow was on identifying the flow regime transition or transition criteria. However, this approach has the following shortcomings:

1. The flow regime transition criteria are algebraic relations for steady-state fully-developed flows. They do not fully reflect the true dynamic nature of changes in interfacial structures. Hence the effects of the entrance and developing flow cannot be taken into account correctly, nor the gradual transition between the flow regimes. Under the microgravity conditions, the flow structure may not reach an equilibrium configuration. Therefore, the flow regime dependent constitutive relations developed for the steady-state fully-developed two-phase flow are not suitable.
2. The method based on the flow regime transition criteria is a two-step method, which requires the flow regime transition criteria and the regime dependent closure relations for the interfacial area.

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3. The flow regime dependent correlations and criteria may be valid only in limited parameter ranges for certain specific operational conditions. When applied to the microgravity two-phase flow conditions, these models may cause significant discrepancies and artificial discontinuities.

To better represent the effects of the interfacial structure and the flow regime transition, the use of the dynamic equation to characterize the interfacial area transport has been proposed and is currently being pursued. Based on the current developments in the normal gravity two-phase flow, the interfacial area transport equation can be considered a rational choice in providing a closure relation for the interfacial area concentration for the microgravity two-phase flow. Through mechanistic modeling of various fluid particle interactions, the interfacial area transport equation can closely model the two-phase flow evolution across the flow regime transition boundaries, and thus prevent artificial discontinuities. Furthermore, the recent studies suggest the significance of investigation on particle interaction mechanisms in the evolution of two-phase structures (Colin et al., 1991; Hewitt, 1996; Takamasa et al., 2002). It is expected that the interfacial area transport equation can significantly improve the current capability of the two-fluid model from both scientific and practical viewpoints.

To benchmark the theoretical model, ground-based tests by employing two immiscible fluids with similar density is being performed to simulate the microgravity condition in the first phase of this research. A detailed scaling analysis is being performed to closely simulate the gas-liquid two-phase flow in the microgravity condition. Both the global and local two-phase flow parameters will be acquired by the state-of-the-art instrumentation, namely, multi-sensor conductivity probes, multi-sensor void-meter, and LDA system, along with detailed flow visualization and image analysis. Following the first stage experiment, the second stage experiment is to be performed with the gas-liquid two-phase flow in the in-flight or drop-tower microgravity facilities.

Currently, the design of the test facility has been basically completed. Through a detailed preliminary study, water and Therminol 59, which has a density of 971 kg/m^3 at 20^{o}C, have been chosen as the two fluids to simulate microgravity environment on ground. Round pipes with 25.4 and 304.8 mm internal diameter have been selected as the test sections. The construction of the facility is expected to be completed and tested by the end of September 2004.

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Two-fluid Model and Interfacial Area Transport under Microgravity Condition

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Research Motivation

- Need of Gas-liquid Two-phase Flow Systems for Future Manned Deep Space Exploration
  - Advanced life support operations
  - Power generation
  - Propulsion
- Limited Understanding of Two-phase Flows under a Microgravity Environment
  - No apparent characteristic internal length scale
  - Flow may not reach an equilibrium configuration
- Predictive Models for Two-phase Flows Developed for Earth Application: Inadequate for a Microgravity Environment
- Previous Research Concentrated on Flow Regime Identification, Pressure Drop Prediction, Pool and Flow Boiling, and Corresponding Scaling Studies

Research Objectives

- To Develop Framework of the Two-fluid Model Formulation with Interfacial Area Transport Equation (IATE) Applicable to Space Microgravity Conditions
- To Perform Liquid-liquid Experiments on Ground to Simulate Two-Phase Flows under Microgravity Conditions
  - To Establish a database of key two-phase flow parameters
- To Develop the IATE Applicable to Microgravity Conditions
  - To model the constitutive relations for the IATE through mechanistic modeling of fluid particle interactions
  - To Investigate the relative motion between phases
- To Study Scaling Issues between Earth and Microgravity Two-phase Flows (Optional)

Technical Approach

- Theoretical Approach
  - Two-fluid Model with IATE
  - Mechanistically modeling of fluid particle interactions
- Experimental Study
  - Simulation of microgravity two-phase flows in earth based on liquid-liquid experiments
    - Two immiscible fluids with similar density
  - Focus on low and medium inertia regions
  - Two sizes of test sections: 2.5 and 30.5 cm ID round Pyrex glass pipes
  - Advanced instrumentation
    - Electrical: Multi-sensor conductivity probe and Impedance void probe
    - Optical: Laser Doppler anemometry and High-speed photography

Two-fluid Model

- Two-fluid Model (Vernier and Delhaye, 1968; Kocamustafaogullari, 1971; Ishii, 1975; Drew and Lahey, 1979)
  - Considers each phase separately
  - Macroscopic fields of one phase are coupled to the other phase
  - Interfacial transfer terms in the conservation equations
- (Interfacial Transfer): ~ (Interfacial Area Conc.) ×(Driving Potential)
- a_i: Interfacial Area Concentration

$$a_i = \frac{\text{Interfacial Area}}{\text{Mixture Volume}}$$

  - Characterizes the geometric "capacity" for interfacial transfer
- Conventional Approach for a_i: Flow Regime-dependent Correlations/Models
  - Flow regime identified by flow regime map or regime transition criteria (Bubbly, Slug, Churn, …)
  - Difficulty of modeling effects of entrance, flow development, and phase change

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Interfacial Area Transport Equation

- Dynamic Approach for Interfacial Structure Modeling, Consistent with the Two-fluid Model (Ishii, '75)
- To Predict Evolution of Interfacial Structures Dynamically
- Foundation of IATE (Ishii and Kocamustafaogullari, '95)
- One-group IATE (Wu et al., '98; Kim, '99)

$$\frac{\partial a_i}{\partial t}+\nabla\cdot\left(a_i\vec{v}_i\right)=\frac{2a_i}{3\alpha}\left[\frac{\partial \alpha}{\partial t}+\nabla\cdot\left(\alpha\vec{v}_g\right)-\eta_{\mathrm{ph}}\right]+\sum_j \phi_j+\phi_{\mathrm{ph}}$$

  - Fluid particle interactions: Coalescence and Disintegration

    (Focus of the current research)
  - Phase change: Nucleation and Condensation

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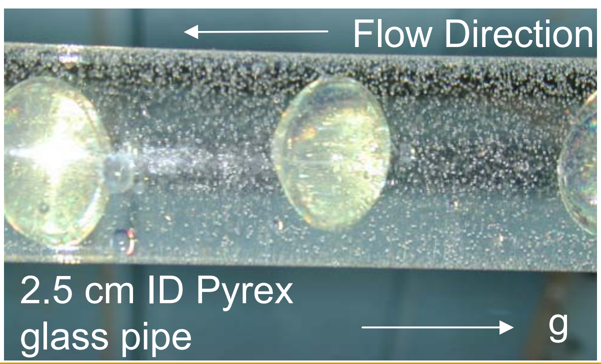
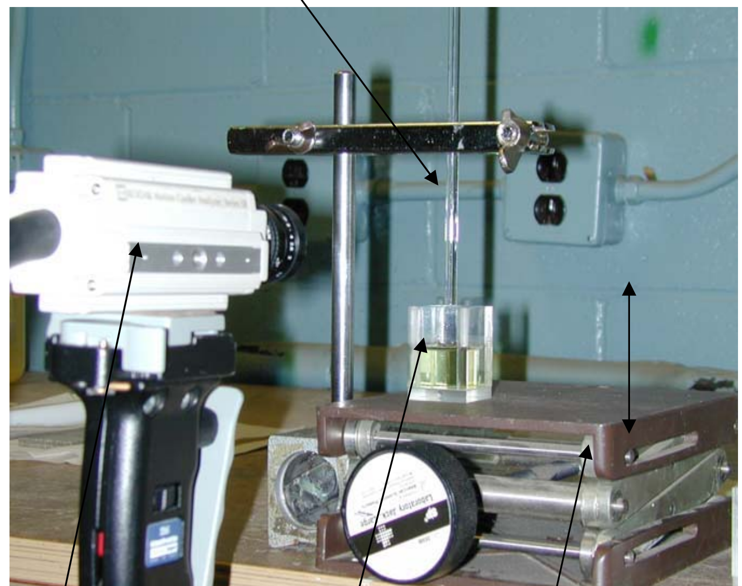
Experimental Study

- Working Fluids
  - Water and Therminol 59 (Alkyl Substituted Aromatic with a density of 971 kg/m^3 at 20^{o}C, 2.7% difference with water)
  - Relatively easy separation based on gravity
  - Interfacial tension measurement (Technique based on Rashidnia *et al.*, '94): $0.037^{+4\%}_{-9\%}$ N/m

Therminol 59 "bubbles" injected into stagnant water



1.2 mm I.D. Pyrex tube



1.25 X 1.25 X 1.75" acrylic test cell

High speed movie camera

Laboratory jack

Present setup for interfacial tension measurement

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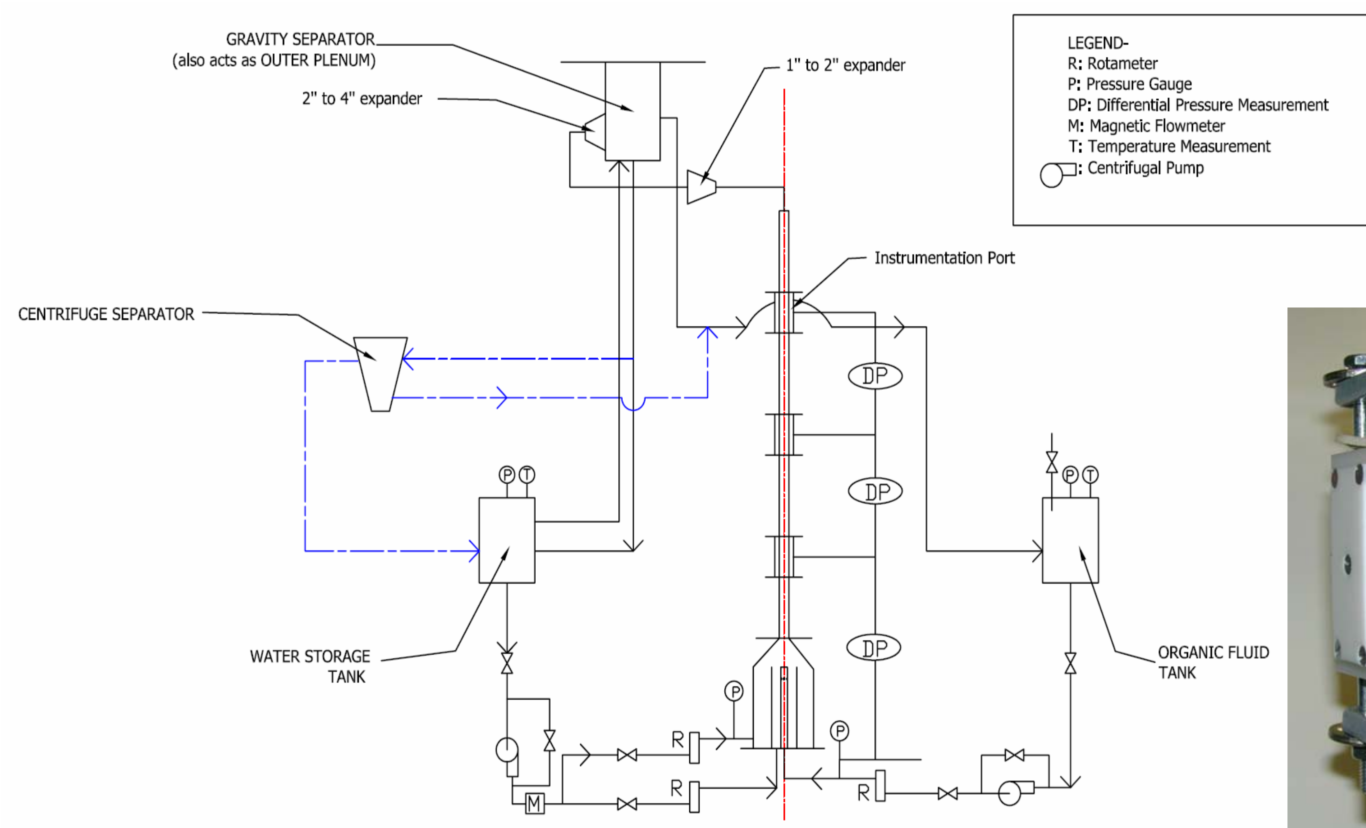
Experimental Facility and Instrumentation



Schematic of the experimental facility for 2.5 cm ID test section

Impedance void probe

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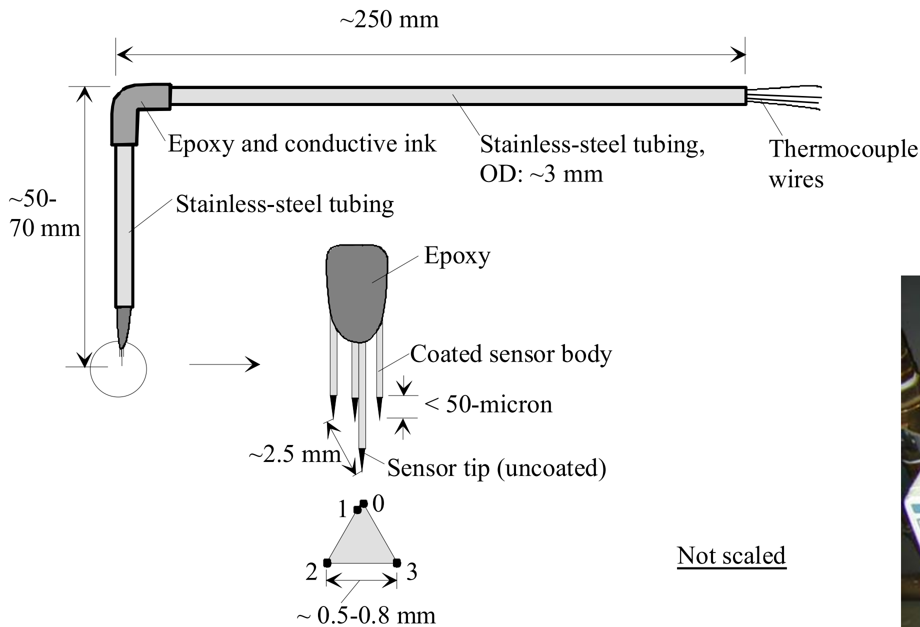
Instrumentation and Data Acquisition



Schematic of four-sensor conductivity probe

Data acquisition

Four-sensor conductivity probe can measure local time-averaged fluid fraction, interfacial area concentration, fluid particle velocity and size

Current Status

- Literature survey has been carried out
- Technical approach has been preliminarily developed
- Possible fluid particle interaction mechanisms have been identified
- Working fluids have been selected
- Experimental facility design has been completed
- Instrumentation has been selected and the applicability has been preliminarily tested
- Surface tension parameter between the working fluids has been measured in house
- Major components of the facility have been purchased or machined
- Construction of the facility is ongoing