University of Ottawa – Stavros Tavoularis CRD

CRD Title: Experimental and Computational Studies of Two-Phase Flows in Nuclear Reactor Systems

Overview

The objective of this project is to evaluate the use of available experimental and computational fluid dynamics (CFD) methods for the study of two-phase flow characteristics in pipes and in a simplified model of a header-feeder system used in CANDU nuclear power plants. The main experimental tasks are: i) to qualify and calibrate a wire-mesh sensor (WMS) for two-phase flow measurements by performing evaluation tests in adiabatic air-water pipe flow; ii) to quantify the measurement uncertainty of the wire-mesh sensor for measuring void fraction, interfacial area and gas velocity; and iii) to compile an experimental database of air-water flow characteristics in horizontal and vertical (upward and downward flow) pipes using the wire-mesh sensor. The main tasks of the computational analysis are: i) to perform CFD simulations of two-phase flows at the same inlet flow conditions and in the same geometries as those of the experiments and to compare the simulation results to the measurements to verify the applicability of CFD as a tool for two-phase flow simulation at the conditions and geometries of interest to nuclear safety analysis; ii) to perform CFD simulations of two-phase flows in a small-scale multi-bank header for which previous experimental results are available. The proposed experimental and numerical investigations are in direct support of the AECL air-water header facility tests. The following sections outline progress achieved during 2013.

Research Facility

The air-water flow loop at the University of Ottawa (Figure 1), which was designed and constructed in the first year of the project, was upgraded in 2012 and, during 2013, this upgraded facility was instrumented with quick-closing valves and pressure transducers to permit the use of other methods of measurement in addition to WMS. A larger pump was installed and the air supply system was reconfigured to extend the operating ranges of water and air flow rates, respectively. Transparent PVC piping was used to replace the acrylic tubing that was used previously, to eliminate occasional breaking and cracking of the pipes due to the violent, oscillatory nature of air-water flow. In the modified facility, measurements can now be made in horizontal, vertical upward and vertical downward air-water flows in all two-phase flow regimes of interest. The apparatus can accommodate WMS, when they are available to us on loan from AECL, but void fraction measurements can also be made at any time with the use of the quick-closing valve technique or the pressure gradient method. A new UNENE CRD, whose objective is to investigate experimentally and computationally air-water flows in simple header/feeder models, has been awarded to the applicant, with the experimental model expected to be commissioned in 2014. The original air-water flow loop is extremely important for this new project. It will serve as the testing and calibration facility for various new methods of experimental measurement and analysis, before they are applied in the more complicated header/feeder geometry.

The principal investigator's CFD laboratory currently comprises four multi-processor servers and two workstation clusters having a total of approximately 300 threads for parallel processing with 600 GB RAM and 6 high-end multiprocessor personal computers for data pre- and post-processing. The applicant maintains licenses of several commercial CFD packages with multi-phase simulation capabilities. In addition, the team makes use of the large-scale, shared computing facilities of HPCVL (High Performance Computing Virtual Laboratory) and RQCHP (Réseau québécois de calcul de haute performance).

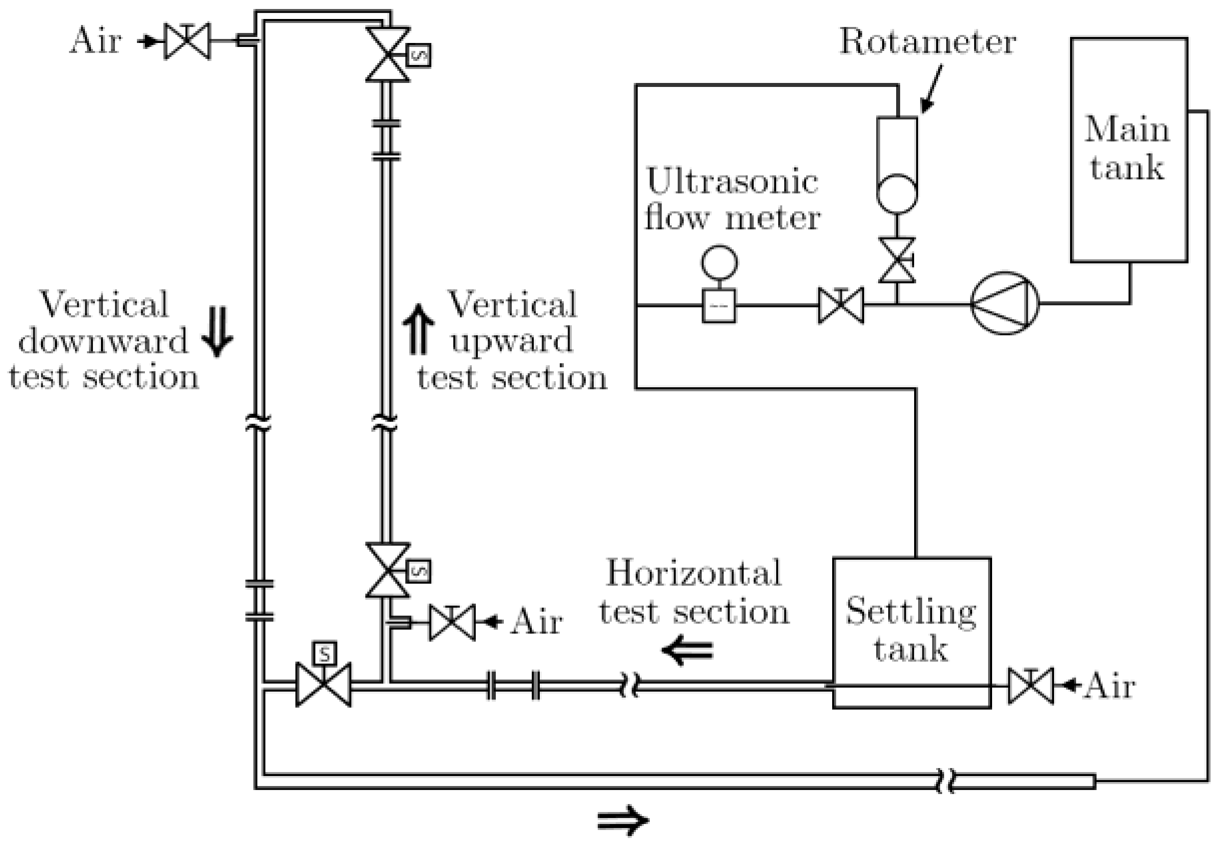

Figure 1: Schematic diagram of the water-air flow loop.

Experimental Results

An extensive database of wire-mesh sensor measurements in horizontal air-water pipe flow has been compiled (flow regime map shown in Figure 2). Void fraction measurements by two wire-mesh sensors, one positioned downstream of the other, were found to be in good agreement at high gas and liquid superficial velocities, but differed significantly at low superficial velocities. For this reason, all reported void fraction measurements were taken with the upstream sensor, which is exposed to a flow that is less disturbed by the intrusion of the device than its downstream counterpart. Interfacial velocity measurements were performed using a pair of wire-mesh sensors in bubbly, slug and plug flows, but not in stratified, wavy and annular flows, in which many nodes of the sensor were never or seldom crossed by the air-water interface. Average interfacial velocity measurements obtained by photography at low void fractions were in good agreement with those from the WMS. The uncertainties of both methods increased with increasing liquid velocity. Drift flux model parameters were proposed based on the overall population of measurements, by flow regime grouping as well as by liquid superficial velocity grouping, and the average percent and RMS differences were determined. This analysis showed that the drift flux parameters were sensitive to the liquid superficial velocity, and that drift-flux models based solely on flow regime would not be sufficient to accurately predict the void fraction over all ranges of flow rate.

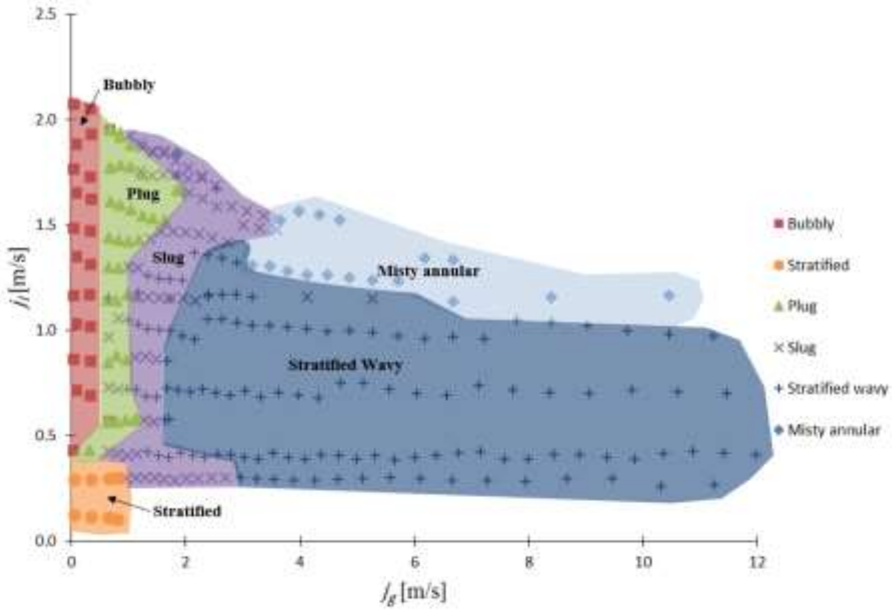

Figure 2: Flow regime map for horizontal air-water pipe flow study.

A new method for the identification of flow regime in vertical upward gas-liquid two-phase flow was also proposed (Figure 3). The method is based on local measurements of differential pressure and analysis of the statistical features of the resulting signal. The machine learning method of elastic maps was used for the first time in this context and proved to be a very accurate and flexible analysis technique for flow regime identification. Differential pressure signals were measured in pipes of three different sizes (13.9 mm, 32.5 mm and 49.2 mm I.D.) and at two different pressures (100 - 140 kPa and 200 - 240 kPa) to demonstrate that this method was not sensitive to pipe size or pressure. This method depends on a local measurement which implies that it is independent of axial location and provides an indication of the local flow regime at the measurement location. Comparison to visual observations of flow regime show that this method can be an unbiased method of flow regime identification of general applicability under different flow conditions without the requirement for *in-situ* calibration.

Computational Work

Following an extensive literature review of experimental and computational studies of gas-liquid flows in pipes, we have evaluated the performance of available CFD codes and models. After testing two commercial codes, CFX 12.1 and FLUENT 12.1, and the open source code OpenFOAM 2.1, it was decided to use OpenFOAM, which is scalable and suitable for parallel processing, permits convenient modifications of its existing models and incorporation of new ones, and can be run, without licensing fees, on our multi-processor computer servers and clusters, as well as on the two Canadian computer networks that we are using currently. The results that we have obtained so far are encouraging, but also point to the need for further testing. As an example, we present results of numerical simulations of horizontal, bubbly, air-water flow in a tube with a diameter of 50.3 mm and a length of 3 m. OpenFOAM 2.1 with the Euler-Euler model was used. Predictions at the tube outlet were in fair agreement with measurements[1] along the vertical line of symmetry (Figures 4).

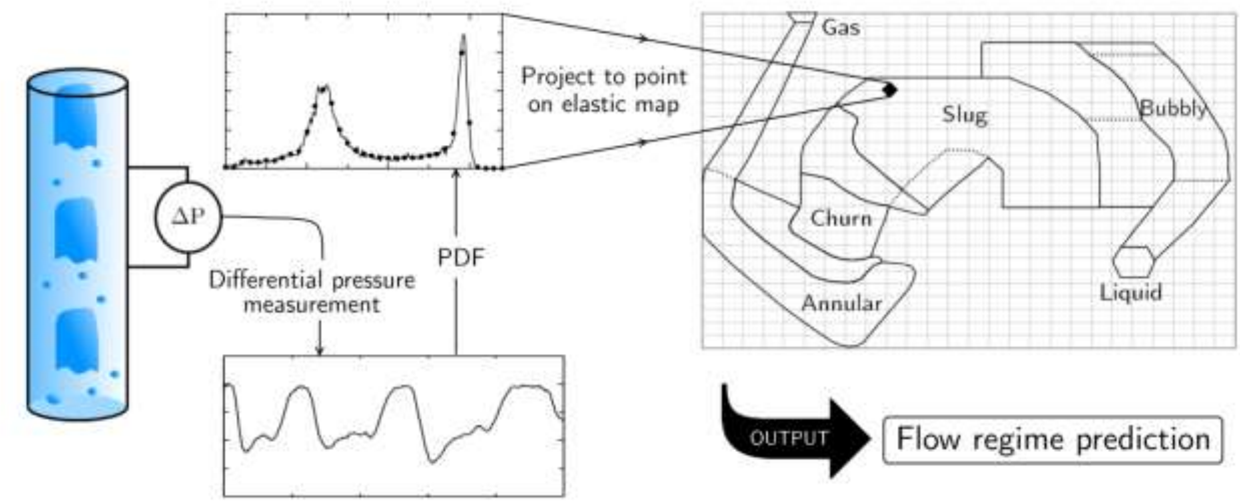

Figure 3: Illustration of newly proposed flow regime prediction method.

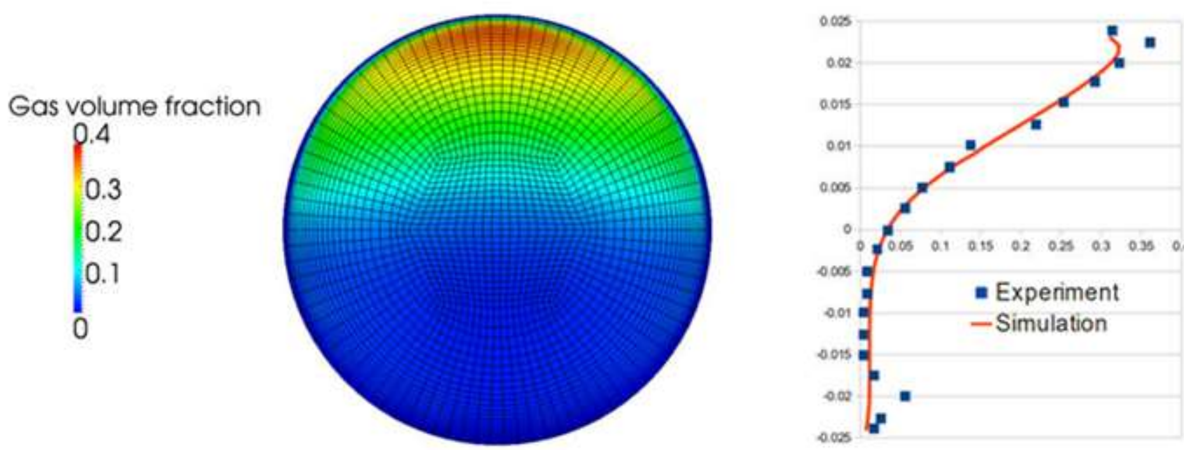

Figure 4: Void fraction map at the pipe outlet (left) and comparison with experiment (right).

An emerging need in industry is the development of best practice guidelines for two-phase flow simulations, similar to those that already exist for single phase flow simulations. The scope of such an undertaking is extremely wide, due to the large number of degrees of freedom present

[1] A. Iskandrani and G. Kojasoy, 2001. *Local void fraction and velocity field description in horizontal bubbly flow*, Nucl. Eng. Des., vol. 204, pp. 117–128.

in any two-phase flow simulation (multi-phase model, turbulence model, interfacial force parameters, discretization schemes, pressure-velocity coupling, mesh size, boundary conditions). However, the problem can be approached by addressing one aspect at a time. To identify the most suitable interfacial force parameters, simulations with different combinations of interfacial forces were performed to find the one most suited to horizontal gas-liquid flows. Air-water flows in a horizontal 3.5 m long, 31.8 mm I.D. tube were numerically simulated and validated against wire-mesh sensor measurements of void fraction performed in the uOttawa air-water flow loop over wide ranges of gas and liquid flow rates. This work is ongoing but representative results for one set of gas and liquid flow rates is shown in Figure 5.

Unfortunately, it was found that, although a set of models and coefficients could work well for one flow case, it could not be generalized to other flows at different flow rates. Hence, there appears to be a need for further development of interfacial force models that are insensitive to flow rate or, alternatively, take into account the effect of flow rate on their variable coefficients.

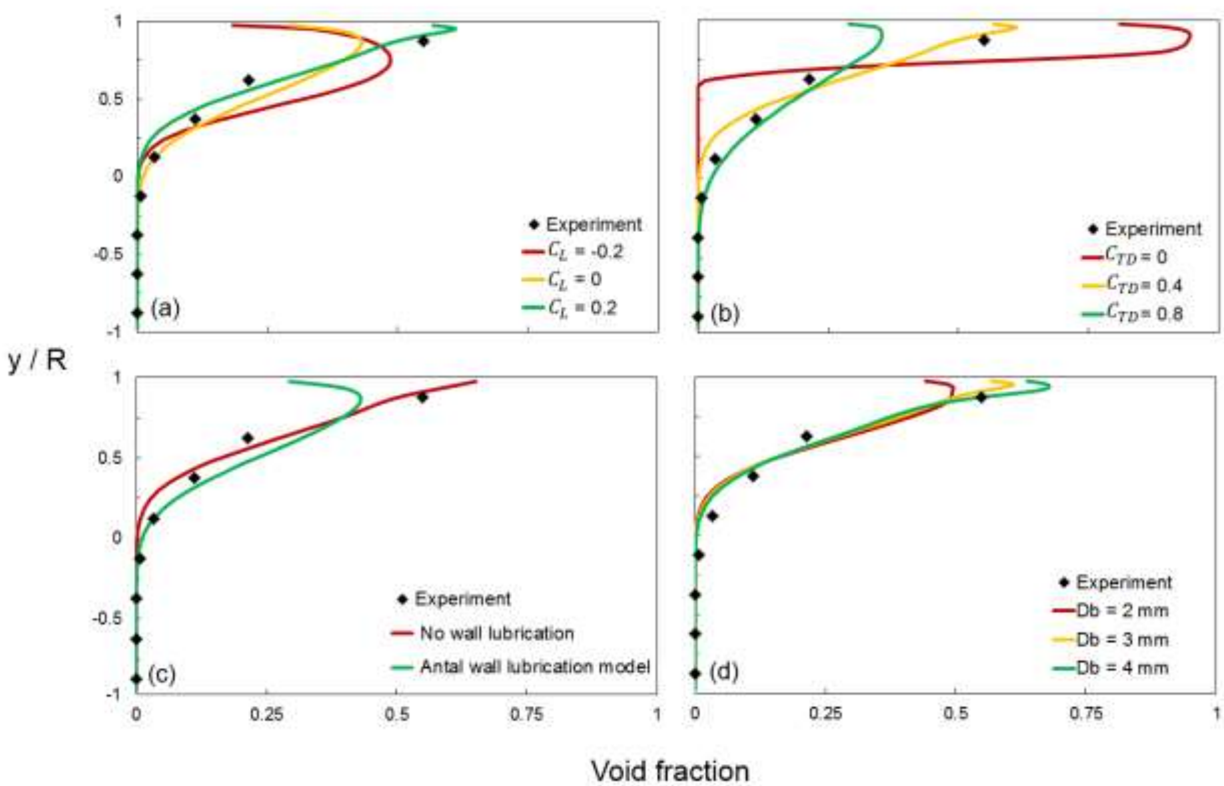

Figure 5: Effect of various model parameters on the radial void fraction distribution in horizontal air-water flow (j_L = 1.66 m/s, j_G = 0.15 m/s); (a) effect of the lift force coefficient, (b) effect of the Bertodano turbulent dispersion coefficient, (c) effect of the Antal wall lubrication force and (d) effect of the bubble diameter.

Training of Highly Qualified Personnel

The following persons have been engaged in this project.

- Hassan Shaban, Ph.D. student (full-time): Experiments and numerical simulations of two-phase flows, application of machine learning methods in the study of two-phase flows.
- Dr. Dongil Chang, Research Associate (part-time): Numerical simulations of two-phase flows.
- Etienne Lessard, M.A.Sc. student (thesis submitted 2013): Construction of the air-water flow loop and measurement of two-phase flow in a horizontal pipe with wire-mesh sensors.
- Dr. Yuan Liu, Research Assistant (completed 2011): Evaluation of multiphase CFD methods.

Interaction with Industrial Partners

The University of Ottawa team is in close contact with AECL staff, particularly Mr. Jun Yang, Thermalhydraulics Development Branch, having frequent discussions concerning research plans and priorities. AECL has provided us with four wire mesh sensors and associated hardware and software. In the past year, our research group has visited the AECL Thermalhydraulics Development Branch in Chalk River to share our progress and to observe the header/feeder facility in operation.

Anticipated Benefits to Industry

During loss of coolant accidents (LOCA), two-phase flow could occur in the CANDU headers and the distribution of the two phases is found to be uneven in the feeder pipes. This could mean that some fuel channels would receive little or no cooling, which may lead to fuel meltdown. This research program aims at producing original measurements and numerical simulations that will enhance the information and tools available to AECL engineers for analyzing the operation and safety of CANDU header systems. In the short term, the results of the project will be used to support the two-phase flow measurements in the header test facility at AECL with wire-mesh sensors. In the longer term, the results will be used to assist AECL staff in performing CFD simulations of the header system and in developing constitutive relations for the two-fluid model to be included in CATHENA 4, the next generation system Thermalhydraulics code being developed by AECL. This research will enable uOttawa to educate several students in nuclear reactor thermalhydraulics, thus providing the nuclear industry with a pool of prospective highly skilled research engineers to replace the currently retiring generation of such personnel, which were mostly hired approximately three decades ago. The students to receive doctorates through this program will also be eligible to pursue academic careers, thus strengthening the few existing Canadian academic programs in Nuclear Engineering and helping establish new ones.

<u>Publications 2012/2013</u>

Some of the results reported during 2013 are as follows:

1. H. Shaban and S. Tavoularis, 2013. Identification of flow regime in vertical upward air-water pipe flow using differential pressure signals and elastic maps, submitted to International Journal of Multiphase Flow.
2. Lessard, E., H. Shaban and S. Tavoularis, 2014. Measurements in Horizontal Air-Water Pipe Flows Using Wire-Mesh Sensors, 2014 Canada-China Conference on Advanced Reactor Development (CCCARD-2014), Niagara Falls, Ontario, Canada, April 27 - 30, 2014 (accepted, November 2013)
3. H. Shaban and S. Tavoularis, 2013. Numerical simulations of air-water flows in horizontal tubes. Thousand Islands Fluid Dynamics Meeting, T.I.M. 2013, Gananoque, Canada.
4. E. Lessard and S. Tavoularis, 2013. Measurements in air-water flows using wire-mesh sensors. Thousand Islands Fluid Dynamics Meeting, T.I.M. 2013, Gananoque, Canada.