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 apply, and further develop, available experimental and computational fluid dynamics (CFD) methods to the study of two-phase flow characteristics in tubes and in header-feeder systems of the type used in CANDU nuclear power plants. The main experimental tasks are: i) constructing a versatile header/feeder model, in which different combinations of active inlet turrets and active feeders can be selected; ii) assembling a database of measurements of gas and liquid flow rates in the feeder tubes of this model, while also documenting the turret inlet conditions and the flow patterns inside the header; and iii) assessing the effect of flow obstructions inside feeder tubes on the gas and liquid flow rates. The main task of the computational analysis is to perform CFD simulations of air-water 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 conditions and geometries of interest to nuclear safety analysis. The proposed experimental and numerical investigations will be conducted using state-of-the-art tools and will advance the technical capabilities of nuclear reactor designers and safety analysts. They are in direct support of the CNL air-water header facility tests.

The project has been very successful and its results have been published in six articles in refereed journals, two graduate theses, eight conference presentations and one technical report. There is accumulating evidence that demonstrates that this work has so far been disseminated extensively and that it is on its way to make an impact in the field. The following sections outline progress achieved during 2016.

Anticipated Benefits to Industry

The research program aims at producing original measurements and numerical simulations that will enhance the information and tools available to CNL 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 CNL with wire-mesh sensors. In the longer term, the results will be used to assist CNL 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 CNL. This grant is enabling uOttawa to educate several students and other highly qualified research personnel 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. As most universities in Canada, USA and elsewhere eliminated or drastically reduced their educational and research programs in Nuclear Engineering, graduates with this type of expertise are needed urgently. Postdoctoral Fellows and 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.

Interactions / Consultations to Industry

The University of Ottawa team is in contact with CNL and CNSC staff, having frequent discussions concerning research plans and priorities.

Research Facilities and Equipment

Experimental facility: A Modular Header Facility was commissioned in Summer 2014 at the University of Ottawa Fluid Mechanics Laboratory (Figure 1). The main component of the facility is a 203 mm I.D. horizontal cylindrical header made of black-anodized aluminium. The header has two inlet turrets, with inner diameters of 32.5 mm and 154 mm, respectively. The larger turret may be capped with a clear acrylic cover, thus permitting visual observation of the header interior. Two additional observation ports made of clear acrylic were installed at either end of the header. Twenty feeder ports with end flanges were arranged in axially equidistant groups of four banks. Each bank consists of five feeder ports, which are connected to the header at three angles of inclination; two ports are horizontal and across from each other, two ports are inclined at 45° below horizontal and one port is vertical, pointing downwards. The header is described as modular, as it permits any combination of feeder ports to be connected to active feeders during an experiment, while the remaining ports are blocked by solid plugs made of polyvinyl chloride (PVC), up to the inside diameter of the header body. The feeders are tubes made of clear PVC with an inside diameter of 32.5 mm. The active feeders are attached to the feeder ports using standard flanges. Beside the header and feeders, the facility comprises a stainless steel water tank, a centrifugal pump and a 32.5 mm I.D. clear PVC inlet line. The liquid and gas flow rates at the inlet turret and in each active feeder are measured by calibrated flowmeters. An array of conductivity probes (Figure 2) was constructed, capable of measuring the void fraction distribution throughout the header.

CFD Laboratory: The principal investigator's CFD laboratory comprises several multi-processor servers for parallel processing, several high-end multiprocessor personal computers for data pre- and post-processing and mass storage devices. In addition, the team makes use of the large-scale, shared computing facilities of CAC (Centre for Advanced Computing) and RQCHP (Réseau québécois de calcul de haute performance). The team has access to commercial and open-source CFD packages with multi-phase simulation capabilities, including Star-CCM+, Nek5000 and OpenFOAM.

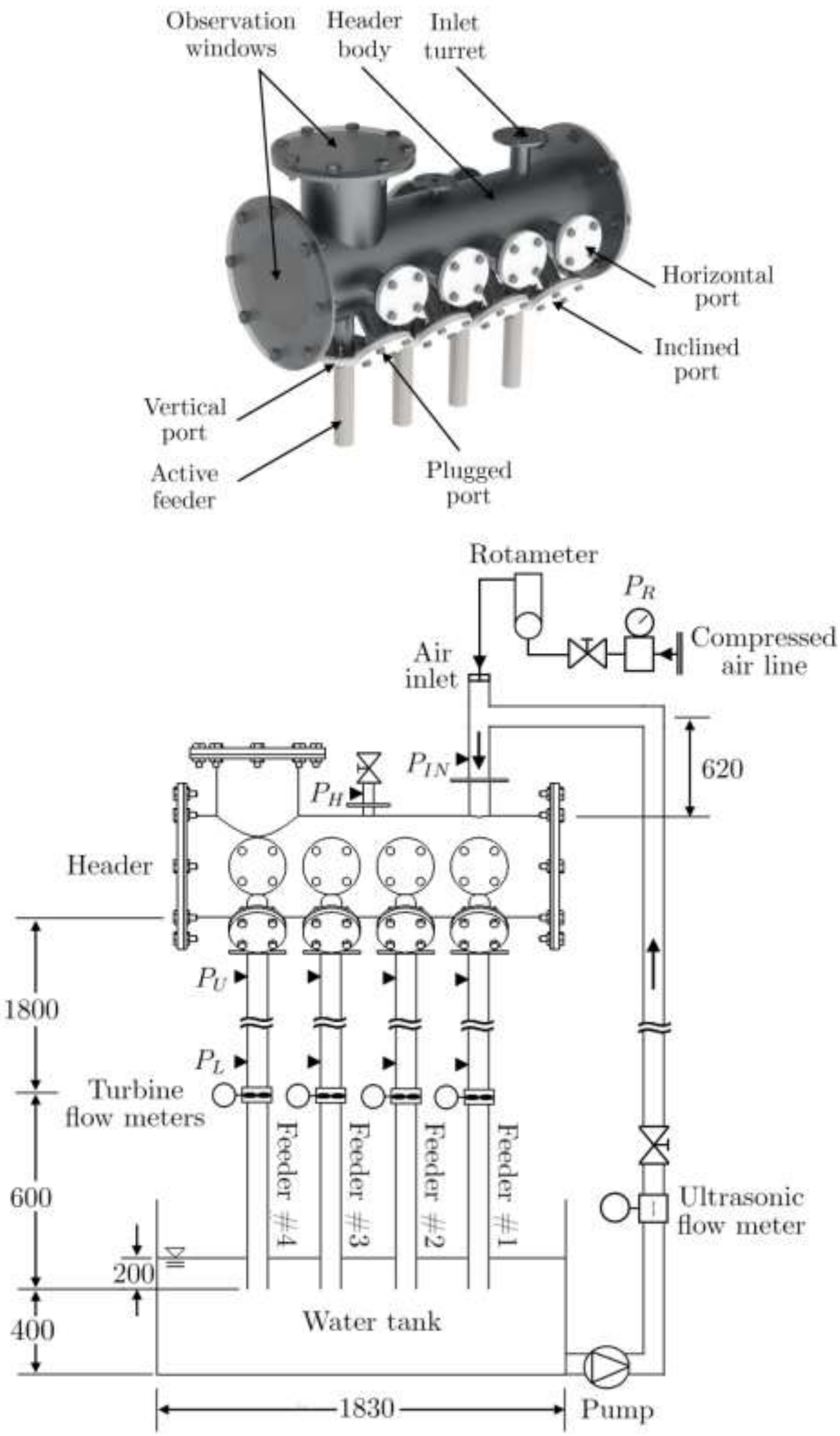
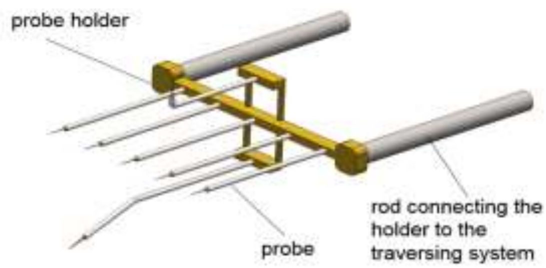


Figure 1. Three-dimensional view of the modular header (top) and schematic diagram of modular header facility (bottom). All dimensions are in mm.



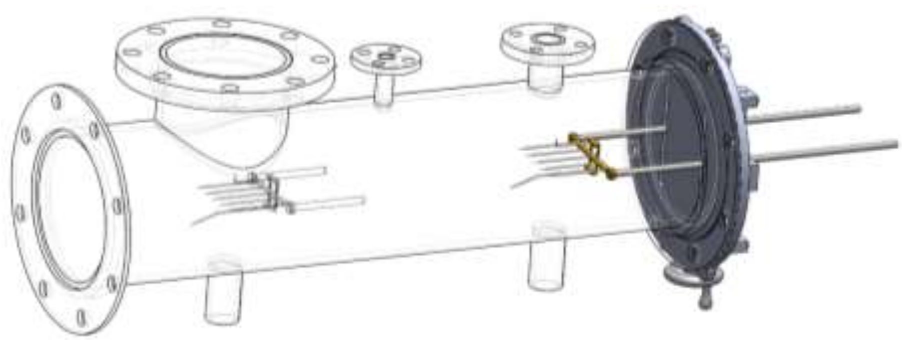


Figure 2. Schematic diagrams of the conductivity probe array (top) and its traversing system in the header (bottom).

Program Results / Highlights

Experimental work: We have developed novel experimental techniques for the identification of the flow pattern and measurement of the flow rates of both phases in gas-liquid pipe flows [2, 5, 12, 13]. These methods are automated, non-intrusive and economical, so that their use would be feasible in industrial as well as laboratory settings. To meet these conditions, we followed an inter-disciplinary approach that combined the use of classical single-phase flow instrumentation, signal analysis and machine learning. We further developed and used similar techniques to measure the two-phase flow distribution in the downward feeders of the University of Ottawa modular header facility [7]. The purpose of this study was to investigate the flow distribution among the feeders of a header-feeder system; an uneven distribution of liquid flow during postulated accident scenarios may introduce safety concerns. The flow patterns in the header and near the feeder inlets were observed visually and were found to depend on the overall gas and liquid flow rates as well as the number and locations of active feeders. The two-phase flow distributions in the feeders were also found to be correlated with the flow patterns in the header. Representative plots of the phase flow rate distributions in a simple header/feeder configuration are shown in Figure 3. Future experiments planned in the Modular Header facility will be aimed at studying the effect of different feeder orientations on the two-phase flow distribution, as well as assessing the effect of flow obstructions inside the feeder tubes on the gas and liquid flow distribution. The conductivity probe array (Figure 2) has been calibrated and is used to investigate the phase distribution and location of the free surface in the header. Preliminary measurements of the average location of the free surface in the header are shown in Figure 4; these results were obtained with the use of the conductivity probe array..

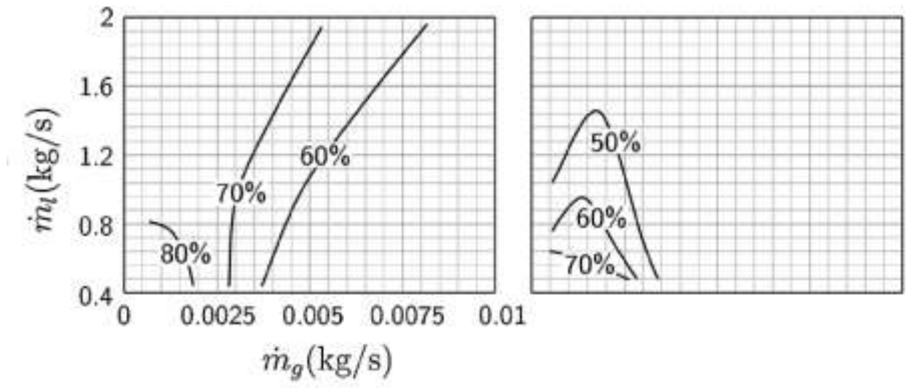


Figure 3. Contour maps of the ratios of liquid (left) and gas (right) mass flow rates through feeder # 1 to the corresponding mass flow rates $\dot{m}_l$ and $\dot{m}_g$ at the inlet turret for cases with the header connected to feeders #1 and #4 only.

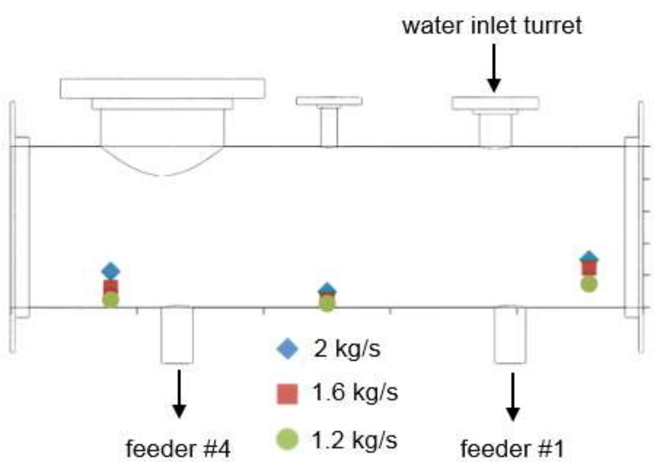


Figure 4. Average location of the free surface in the header centreplane for three different inlet liquid mass flow rates and with the header top open to the atmosphere. Only feeders #1 and #4 are active in this case.

Computational work: 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. We have evaluated a variety of CFD models implemented in commercial and open source CFD codes for several flow configurations, including the flow of Taylor bubbles rising in stagnant liquid columns [1]. The chosen approach was the use of Detached Eddy Simulation (DES) with the Volume Of Fluid (VOF) model. The objective of this study was to shed light on the turbulence and heat transfer characteristics of two-phase slug flow. The flow structures that influence the coalescence of consecutive Taylor bubbles was also investigated. Some representative results are shown in Figure 5. The same CFD approach has been applied to the simulation of the two-phase flow in the modular header-feeder with different feeder configurations. Several cases have been completed and several others are in progress. The predictions of liquid flow rate through each feeder are in fair agreement with the measured values. Representative results are shown in Figure 6.

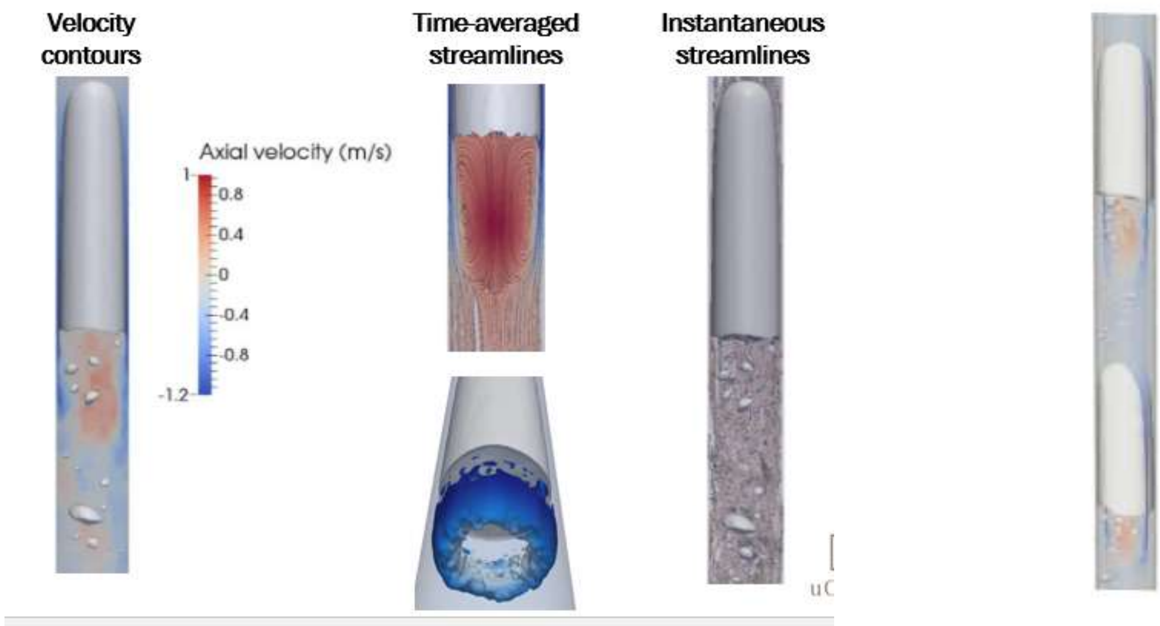


Figure 5. Velocity field about a Taylor bubble rising in a stagnant water column (three leftmost plots) and tendency of two Taylor bubbles to merge (right plot).

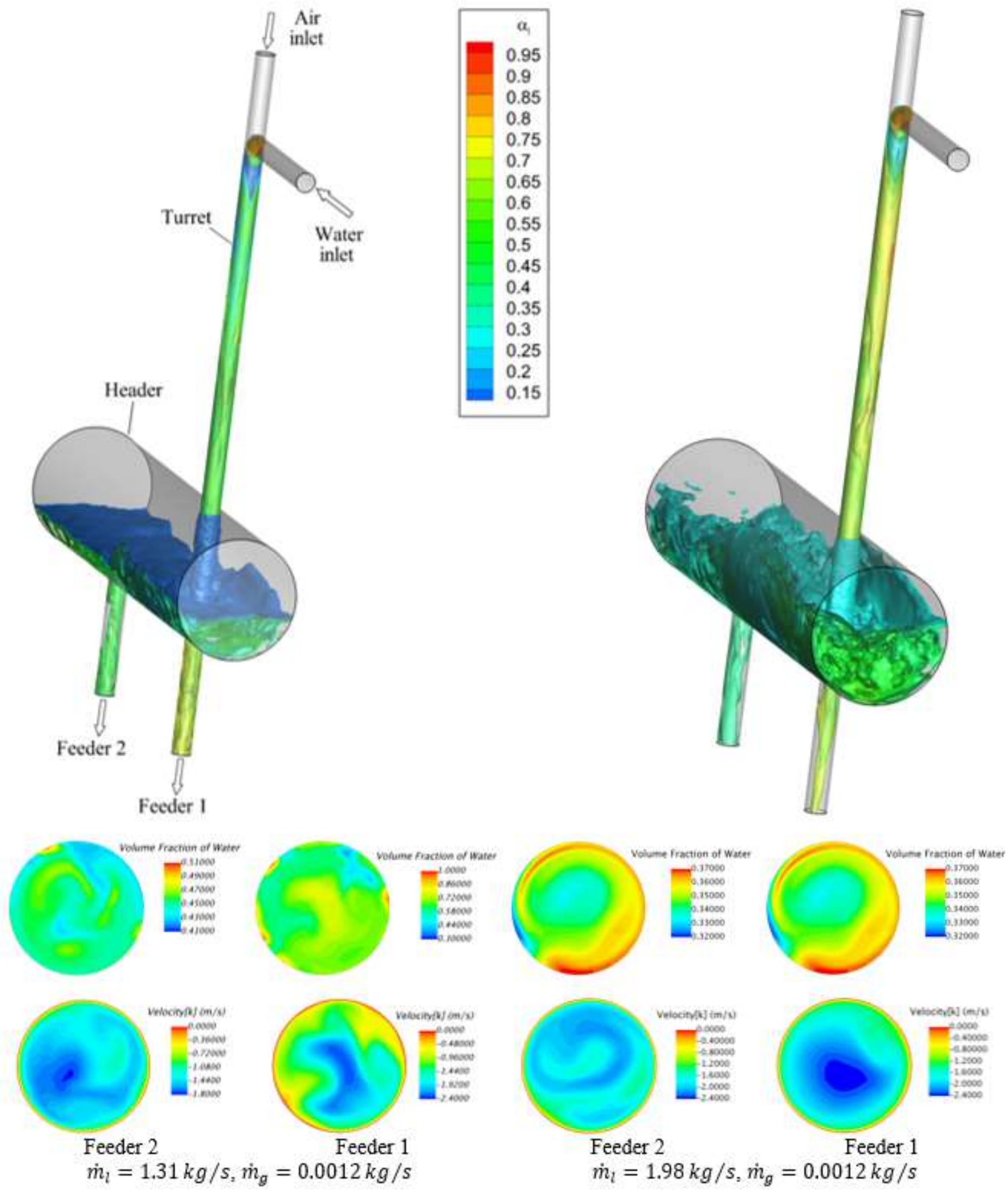


Figure 6. Representative snapshots of the free surface in the header (top) and axial velocity contours at the exit planes of the two active feeders (bottom).

Training of Highly Qualified Personnel (HQP)

The following persons have been engaged in this project.

- Dr. Hadi Moradi, Postdoctoral Fellow (full-time, started July 2016): Numerical simulations of air-water flows in a header-feeder system.
- Azim Bin Mohd Arshad, Ph.D. candidate (full-time, started January 2016): Measurements in flows of air-water mixtures in a header-feeder system.
- Armel Don, Research Assistant (part-time, January - May 2016): Design and construction of multi-probe void fraction measurement system. *Current Employer:* Linamar Corporation.
- Harun Oria, Ph.D. candidate (full-time, January 2015 - April 2016): Experiments and numerical simulations of two-phase flows. *Current Employer:* Unknown.
- Dr. Hassan Shaban, Ph.D. (completed 2015): Experiments and numerical simulations of two-phase flows in pipes and in header-feeder systems, application of machine learning methods in the study of two-phase flows. *Current Employer:* ICF International.
- Dr. Dongil Chang, Research Associate (part-time, completed 2015): Numerical simulations of two-phase flows. *Current Employer:* Altair Engineering Inc.
- Etienne Lessard, M.A.Sc. (completed 2013): Measurement of two-phase flow in horizontal pipes with wire-mesh sensors. *Current employer:* Canadian Nuclear Laboratories (CNL).
- Dr. Yuan Liu, Research Assistant (completed 2011): Evaluation of CFD methods for two-phase flows. *Current employer:* Life Prediction Technologies Inc.

Publications / Journal Papers

1. Shaban, H. and Tavoularis, S., **2017**. "Thermal characteristics of Taylor bubble flow." 10th International Conference on Thermal Engineering: Theory and Applications, February 26-28, 2017, Muscat, Oman.
2. Shaban, H. and Tavoularis, S., **2017**. "Performance evaluation of conductivity wire-mesh sensors in vertical channels." Flow Measurement and Instrumentation 54, 185-196.
3. Bin Mohd Arshad, A. and Tavoularis, S., **2017**. "Study of water-air interface in a horizontal cylindrical header using conductivity probes." Thousand Islands Fluid Dynamics Meeting, Gananoque, Canada.
4. Vafadar Moradi, H., Shaban, H. and Tavoularis, S., **2017**. "Numerical simulation of air-water flow in a header-feeder system." Thousand Islands Fluid Dynamics Meeting, Gananoque, Canada.
5. Shaban, H. and Tavoularis, S., **2016**. "On the accuracy of gas flow rate measurements in gas–liquid pipe flows by cross-correlating dual wire-mesh sensor signals." International Journal of Multiphase Flow 78, pp. 70-74.
6. Shaban, H. and Tavoularis, S., **2015**. "The wire-mesh sensor as a two-phase flow meter." Measurement Science and Technology 26, 015306 (16 pp).
7. Shaban, H. and Tavoularis, S., **2015**. "Distribution of downward air-water flow in vertical tubes connected to a horizontal cylindrical header." Nuclear Engineering and Design 291, pp. 90-100.
8. Shaban, H. and Tavoularis, S., **2015**. "Detached eddy simulations of Taylor bubbles rising in stagnant liquid columns." Bulletin of the American Physical Society 60 (21): 68th Annual Meeting of the APS Division of Fluid Dynamics, D9.00003 (1 pp.).

9. Shaban, H. and Tavoularis, S., **2015**. “Zorbubbles: Producing flow regimes in air-water flow.” Video entry, APS Gallery of Fluid Motion, http://gfm.aps.org/meetings/dfd-2015/55e1b23a69702d060d0e0000.
10. Shaban, H., **2015**. “Experimental investigations of internal air-water flows.” Ph.D. thesis, University of Ottawa, Ottawa, Canada.
11. Oria, H., H. Shaban and S. Tavoularis, **2015**. Air-water flow distribution in multiple vertical tubes branching from a horizontal header. Thousand Islands Fluid Dynamics Meeting, T.I.M. 2015, Gananoque, Canada.
12. Shaban, H. and Tavoularis, S., **2014**. “Measurement of gas and liquid flow rates in two-phase pipe flows by the application of machine learning techniques to differential pressure signals.” International Journal of Multiphase Flow 67, pp. 106-117.
13. Shaban, H. and Tavoularis, S., **2014**. “Identification of flow regime in vertical upward air-water pipe flow using differential pressure signals and elastic maps.” International Journal of Multiphase Flow 61, pp. 62-72.
14. Lessard, E., Shaban, H. and Tavoularis, S., **2014c**. “Measurements in horizontal air-water pipe flows using wire-mesh sensors.” 2014 Canada-China Conference on Advanced Reactor Development (CCCARD-2014), Niagara Falls, Canada, 27 - 30 April, 2014.
15. Shaban, H. and Tavoularis, S., **2014**. “Identification of flow regime in air-water pipe flow using differential pressure fluctuations and elastic maps.” Thousand Islands Fluid Mechanics Meeting, Gananoque, Canada, 30 May - 1 June, 2014.
16. Lessard, E., **2014**. “Measurements in horizontal air-water pipe flows using wire-mesh sensors.” M.A.Sc. Thesis, University of Ottawa, Ottawa, Canada.
17. Shaban, H, and Tavoularis, S., **2014**. “Development of drift-flux models for evaluating two-phase mass flow rates in a header facility.” Technical Report UO-MCG-DFM-2014-01 (110 pp.), University of Ottawa, Ottawa, Canada.