Executive Summary

Progress updates on each research project are provided in this Advisory Board meeting brochure. A brief summary of the activities is given below.

- *"Up-Scaling Studies."* One of the most important issues faced in multiphase flow technology development is scaling up small diameter and low pressure results to large diameter and high pressure conditions. The main objective in this study is to investigate the effect of pipe diameter and pressures on flow behavior using the newly constructed 6-in. ID high pressure flow loop. Several studies will be conducted under this project line. The first TUFFP study utilizing this new facility is *"Pressure Effects on Two-Phase Oil-Gas Low Liquid Loading Flow."*

  1. *"Pressure Effects on Two-Phase Oil-Gas Low Liquid Loading Flow in Horizontal Pipes."* The main objectives of this project are to acquire experimental data for low liquid loading two-phase flow in a 6-in. ID pipe at elevated pressures, evaluate existing closure relationships and models based on experimental data, and improve existing models or develop new ones if needed.

     During this reporting period, once again significant progress was made. Full test matrix at operating pressure of 300 psig and partial test matrix at operating pressure of 400 psig were completed. The acquired data included high-speed and high-definition video recordings, pressure gradient, liquid holdup, wetted wall fraction, liquid film height and liquid entrainment. The experimental liquid holdup and pressure gradient measurements were compared against various correlations and models. The experimental wetted wall fraction and entrainment fraction measurements were compared with several available models. Acquired data at three different operating pressures were compared to see the effects of pressure on flow pattern, pressure gradient, liquid holdup, wetted wall fraction, liquid film height and liquid entrainment. Testing will be completed in 2015.

  2. *"Pressure and Inclination Effects on Low Liquid Loading Two-Phase Flow in Near-Horizontal Low Liquid Loading Pipes."* The main objectives of this project are to acquire experimental data for low-liquid.

     After completion of the horizontal flow tests, the facility will be inclined and the effect of pipe inclination on the flow under high pressure conditions will be investigated. This study is assigned to Mr. Hendy Rodrigues, a Ph.D. student of TUFFP. At higher gas flow rates, where stratified and annular flow are expected, the closure relationships for liquid holdup, entrainment, pressure gradient, etc. will be evaluated and modified, if needed. At low gas flow rates, liquid is expected to accumulate at the lower parts of the pipe and pseudo-slugs may be formed. In this case, the characteristics of waves and pseudo-slugs (celerity, length, frequency, etc.) will be measured. The results will be compared to previous works and new models will be proposed, if needed.

  3. *"Upscaling Modeling Using Dimensional Analysis in Gas-Liquid Annular and Stratified Flows."* As part of upscaling studies, Dr. Abdel Al-Sarkhi has developed an upscaling model based on dimensional analysis for stratified and annular flows during his summer stay at TUFFP. The model was validated and showed a good agreement with experimental data available in literature and with new experiments from TUFFP's high pressure facility. The model was also validated using high pressure data (where experimental data are not available) generated from OLGA simulator.

  4. *"New Dimensionless Number for Gas-Liquid Flow in Pipes."* One of the ways of upscaling is through dimensionless numbers that can represent the physics of a process. For multiphase flow in pipes, it has always been challenging to find a universal set of dimensionless numbers. During this summer, we have developed a new dimensionless number we call Slip Number. A detailed presentation and summary report are provided in this brochure.

- *"Onset of Liquid Accumulation in Oil and Gas Pipelines."* Accumulation of liquid, oil and/or water at the bottom of an inclined pipe is known to be the source of many industrial problems, such as corrosion and terrain slugging. Accurate quantification of the required gas velocities to efficiently sweep the water out and prevent accumulation and accurate prediction of oil and water holdup are of great importance. Currently, minimum gas velocity or critical angle requirements, which are often very conservative, are being implemented with various success rates to prevent corrosion in multiphase pipelines. An experimental and theoretical modeling project is underway to better quantify the accumulated liquid volumes and the critical gas velocity/inclination angle. TUFFP's 3-in. ID three-phase flow facility was used for the experimental portion of this study.

  During this period, all hilly-terrain tests have been completed. A modeling study of onset of liquid accumulation has been conducted and a new model developed. Moreover, a modeling framework for pseudo-slug flow is proposed.

During the next reporting period, the proposed onset of liquid accumulation model will be further evaluated and improved and a pseudo-slug flow model will be developed.

- "*Water Cut and Pipe Diameter Effects on Liquid Accumulation.*" At horizontal and low inclination angles, stratified flow is observed under low liquid loading conditions. With the presence of water, a continuous water film at the bottom can cause pipe corrosion. In upward inclined pipes, the gravity effect on liquid film can result in liquid accumulation which impacts pipe corrosion and slugging behavior. The criteria to determine the conditions to avoid liquid accumulation have been the interest of the oil industry.

  The previous and current research studies are limited to small pipe diameters and/or two-phase flow. This project was started to study the effect of pipe diameter scale up (6-in pipe) for two-phase and three-phase flow at 2° inclination. In addition, the effect of water cut and water film distribution in three-phase flow will be investigated for ±2° inclinations and horizontal pipe.

- *"Oil Viscosity Effects on Two-Phase Flow Behavior."* Earlier TUFFP studies showed that the performances of existing models are not sufficiently accurate for high viscosity oils with a viscosity range of 200 – 1000 cp.

  TUFFP's efforts resulted in the development of new translational velocity, slug liquid holdup and slug length closure relationships. Moreover, the TUFFP unified model was modified for high viscosity oil two-phase flow based on the experimental findings. This project continues on multiple fronts for further betterment of the model performances:

  1. *Oil-Gas Flow Behavior in Upward Vertical and Highly Deviated Pipes:* The objective of this study is to investigate high viscosity oil-gas flow in vertical and deviated wells for a viscosity range of 180 – 587 cp. TUFFP's 2-in. ID three-phase flow facility is being used for this project. Initially, vertical flow configuration was studied.

     During this period data acquisition was continued for ±5° and ±10° inclination angles. Calibration of QCV system for inclined flow was completed. The data processing algorithm was debugged. The data of for ±5 have been analyzed. Various models were tested against the data.
  2. *Detailed Flow Field Analysis of High Viscosity Oil-Air Slug Flow:* TUFFP recently purchased a Particle Image Velocimetry (PIV) device to measure velocity fields in multiphase flow. It is now utilized to investigate velocity fields in high viscosity oil and air slug flow. The primary objective is to better understand the physics of the flow. This understanding is expected to inspire better modeling of slug flow for high viscosity oils. Preliminary results presented at this Advisory Board meeting reveal new information about high viscosity oil and gas slug flow and potential of PIV equipment for two-phase flow applications. However, some PIV measurement challenges are identified and potential solutions are proposed. These will be addressed, and results will be reported at spring 2016 ABM.
  3. *"Positive Frictional Pressure Gradient in Vertical Slug Flow."* The existence of positive pressure gradient in vertical slug flow of high viscosity oil and air has been experimentally shown by Al-Ruhaimani (2015). The objective of this short-term study was to provide a theoretical and experimental verification and general occurrence criteria of the positive frictional pressure gradient. The study has already been completed.

     The positive pressure gradient in a vertical slug flow phenomenon is explained. Qualitative wall shear stress model in the Taylor bubble zone and the slug body zone is developed to explain the sources, reasons and conditions of this phenomenon. The phenomenon is neither a violation to the second law of thermodynamics nor a measurement uncertainty/an unrealistic result to be avoided. The total wall shear stress in the slug unit which consists of liquid slug and Taylor bubble is the summation of two opposite wall shear stresses. The liquid film flows downward and the liquid slug flows upward. Based on the magnitude of those two opposite shear stresses, the positive pressure gradient may appear. Thus, the total pressure drop is always positive (negative total pressure gradient). However, the frictional pressure drop could be positive or negative depending on the wall shear stress.
  4. *Medium Viscosity Oil Study:* Brito (2012) recently completed an experimental study for horizontal pipe flow covering an oil viscosity range of $20cP<\mu_O<200cP$. After the completion of the PIV study, medium viscosity tests are planned for inclination angles of -2° and +2°.

- *"Unified Mechanistic Model."* TUFFP maintains and continuously improves the TUFFP Unified model. The emphasis has been on modularity and computation efficiency. Now, any closure relationship can be used with TUFFP Unified model. This brochure contains a presentation outlining the progress during this reporting period.

- *"3-in. ID Three-Phase Flow High Pressure Facility Development."* Based on TUFFP Questionnaire results and availability of funds to complete the instrumentation, this facility will be assigned to a TUFFP project.

- "*TUFFP Experimental Database Development."* The main objective of this project is to construct a comprehensive multiphase flow database of TUFFP experimental data sets.

  Schlumberger already developed a steady-state multiphase database software using Microsoft Access, which was donated to TUFFP. The platform is changed from Access to Excel for easier data incorporation. As of August 2015, FFPDB has 59 experimental data sets with 14,010 data records. The database consists of 42 gas-liquid data sets, 11 oil-water data sets, and five gas-oil-water data sets. Efforts are underway to expand the database beyond TUFFP data.

- *"Unified Model for Oil-Water Flow."* There are predictive models developed for either horizontal, slightly inclined, or vertical upward flows of oil and water in pipes. There is a need for a unified model to predict the flow behavior. This project ranked high in the TUFFP Questionnaire. Therefore, we have initiated this as an active project recently. The objective of this project is to develop a new oil-water unified model for flow pattern, pressure drop, and water fraction prediction applicable for inclination angles from horizontal to vertical flow.

- "*Application of Advanced Measurement Techniques on Multiphase Flow Research."* The main objective of this project is expanding the existing experimental capabilities of TUFFP with advanced measurement techniques to obtain detailed information on flow topology and flow field with an improved confidence level.

  TUFFP already implemented the Canty Visualization Device into the 6-in. ID high pressure flow loop. This device is now proven to produce both qualitative and quantitative flow characteristics.

  The wire-mesh device (WMD) developed by HZDR was successfully tested in the 6-in. ID low pressure flow loop for air-oil flow, and later incorporated into the 6-in. ID high pressure facility to provide flow topology information. A 3-in. ID WMD device was successfully used in TUFFP's 3-in. ID low pressure facility for air-water flow.

  Based on 3-in. and 6-in. ID pipe WMD data, new insights on closure relationships for separated two-phase flows have been realized. These insights will result in new and better closure relationships as well as new modeling directions. A detailed presentation is provided at this Advisory Board meeting.

  For detailed flow field measurement, a PIV device was recently purchased from TSI and will initially be used in the 2-in. ID high viscosity oil facility. The PIV device will enable us to measure the local velocities at a given cross-section of the pipe.

TUFFP membership increased to 18 for 2015. Two of the members informed us that they will not renew their membership for 2016. Therefore, 2016 membership currently stands at 16. Efforts continue to further increase the TUFFP membership level. Two new companies showed interest in joining TUFFP for 2016. A detailed report on membership and financial matters is provided in this brochure.

Several related projects are underway. These related projects involve sharing facilities and personnel with TUFFP.

Tulsa University Paraffin Deposition Projects (TUPDP) continues into its fifth three-year phase. TUPDP membership increased to 11 with CNOOC's joining.

The Tulsa University Horizontal Well Artificial Lift Projects, TUHWALP, is addressing the artificial lift needs of horizontal wells drilled into gas and oil shales. TUHWALP started its activities in July 2012. The current membership stands at 18.