

Final Report

on

Gas-Liquid Flow in Pipelines

7/1/86 to 7/31/04

by

Thomas J Hanratty
University of Illinois
Urbana, IL 61801

to

U.S. Department of Energy
Division of Materials Science
and Engineering

Grant DEFG02-86ER13556

1. Background

Gas Liquid flows are ubiquitous in engineering practice and in the environment. Quite often, success or failure of a process depends on our ability to handle these flows. Many new technologies have been confronted with multiphase problems: the design of offshore gas and oil pipelines, the design of a space station, the prediction of heat transfer characteristics of new refrigerants, the operation of the Alaska pipeline, the safe operation of water-cooled nuclear reactors, designing for thermal stresses in new condensation/evaporation processes, the development of processes for making synfuels. Despite the importance of multiphase flows, their understanding is primitive compared to single phase flows. The need to identify and understand basic scientific principles and basic processes which underlie the behavior of these systems represents the motivation for this research project. The long range objective is to participate in the development of an approach which describes macroscopic behavior in terms of small scale interactions. The role of the principal investigator in promoting this approach was recognized in 1998 with his receipt of the first International Prize on Multiphase Flow.

The particular focus of this proposal is the analysis of gas-liquid flow in a pipe. This provides a simple system in which to study basic interactions. Furthermore, many of the results can find direct application. The study of flow in a pipe is a starting point for a scientific treatment of gas-liquid flows, as was Poiseuille's law and measurements of fully-developed flows, a starting point for the analysis of single phase flows. Furthermore, the enhancement of basic understanding of gas-liquid flow in a pipe in recent years improves our analytical tools and offers the opportunity for significant advances.

The reason for the difficulty in dealing with these flows is that the interface between the phases can take on complicated configurations. For example, air and water flowing in a long horizontal pipe, can have a stratified configuration at low gas and liquid velocities whereby the liquid flows along the bottom of the pipe and the gas concurrently with it. At higher gas velocities waves that form at the interface can have a strong effect on the pressure drop. At high liquid rates and low gas rates long bubbles form at the top of the pipe. At high liquid rates and high gas rates a pattern is exhibited whereby slugs of highly aerated liquid move down the pipeline at the gas velocity. This slug pattern is often avoided since it causes undesirable equipment vibrations. At very high gas velocities an annular pattern is observed, whereby part of the liquid flows along the pipe as a film and part, as droplets entrained in the gas flow. In this annular flow regime there is an exchange of liquid between the wall layer and the drops in the gas core. At very high gas velocities a homogenous bubbly or foam pattern exists.

The phenomena that need to be understood to provide physical descriptions of the flow outlined above are the generation of waves, the behavior of drops and bubbles in a turbulent fluid and various interfacial interactions (such as the formation and breakup of drops and bubbles). For a number of years this laboratory received support from the National Science Foundation to study these basic problems. Over the period 1973-1985 the Design Institute for Multiphase Processing provided seed money to use knowledge gained in these basic studies to provide a basic theoretical approach to gas-liquid flow problems. The award of a Shell Distinguished Chair in Chemical Engineering over the period 1981-1986 gave a strong impetus

– particularly from the viewpoint of the development of the special flow facilities and experimental techniques that we are now using. In 1986 the Department of Energy initiated support for new work.

Our viewpoint is that studies of wave generation, particle turbulence and interfacial processes could be sterile if they are not directly used to provide a quantitative description of phenomena that are observed in gas-liquid flow systems. Furthermore we feel that an examination of the impact of our basic studies on the analysis of industrial systems provides a calibration of our success. The work performed in this research has, as already indicated, broad applications. However, in order to test our progress and to establish priorities, we have focused, mainly, on problems related to the petroleum industry. In 1996 a dialogue was initiated with the production group of Shell Technology in which we identified aspects of the basic research at the University of Illinois which could have an important impact on their engineering activities: (1) prediction of flow patterns which will occur under conditions that prevail in practice, (2) prediction of the fraction of liquid entrained in the gas in annular flow, (3) prediction of slug frequency, (4) prediction of pressure drop and hold-up. This collaboration has continued. Over the period 1998-2000 the PAIR (Partners in Academic and Industrial Research) program of DOE provided \$50,000 per year to facilitate this collaboration.

2. Scope

Thus, the goal of the work described in this report was to establish the basic scientific tools that are needed to understand and calculate the behavior of gas-liquid flows. The specific approach that has been taken was the development and implementation of theories for the transitions from one pattern to another and for how the phases distribute in a given pattern. A description of phase distribution based on physical understanding of small scale interactions can provide a means to calculate frictional pressure drop, liquid hold up, heat transfer rates, reaction rates and other quantities of interest. However, another interest on our part is to use this understanding to determine methods for changing flow patterns. Our use of drag-reducing polymers is an example.

The physical analysis outlined above will have an impact on computational methods to deal with more general gas-liquid systems than flow in a pipe, since the approach being taken is to develop correlations based on physical hypotheses about the interaction at fluid-fluid and fluid-solid interfaces, rather than on straightforward empiricism.

The approach that we took required that we address a number of specific problems. In annular flow we need to understand the rate of atomization of liquid from the wall film, the rate of deposition of drops on to the wall film, the factors governing drop size distribution, the influence of gas phase turbulence and gravity on the behavior of drops, the physics which determines how a liquid film spreads around the circumference of a horizontal or slightly inclined pipe. The gas blowing over a liquid surface can produce waves by different mechanisms. A basic understanding of these mechanisms and a definition of the parameters governing wave height are needed to understand flow regime transitions and interfacial drag in stratified and annular flow. An understanding of the motion of large bubbles in a horizontal

pipe enters into the determination of whether a slug is stable and the determination of how a slug pattern evolves. A number of poorly understood phenomena, such as the coalescence of waves, enter into a scientific explanation of how slugs are formed. We believe that a more detailed physical description of a slug will be needed to predict frequency of slugging and the transition from a slug pattern to an annular pattern.

3. Accomplishments

Our accomplishments are summarized in the (72) published articles that are listed at the end of this report:

(a) Flow regimes. The mechanisms for the transition from one pattern to another in a horizontal pipeline were studied (122, 137). Of particular interest is the definition of a pseudo-slug regime and the development of techniques to differentiate between slugs and pseudo-slugs (123, 228). It was demonstrated that the addition of very small amounts of drag-reducing polymers can qualitatively change the flow pattern by damping waves and by damping turbulence (212, 215, 223, 232).

(b) Waves. Basic studies of wave generation were carried out (125, 131, 145, 170, 183, 193). The direct relation of interfacial drag to wave height was demonstrated (136, 230, 231). The influence of waves on interfacial transport was studied (161, 162, 176).

(c) Effect of pipeline inclination. A mechanistic study was carried out on the effect of small pipeline inclinations on flow patterns (207, 210).

(d) Mechanisms for transition. It has been demonstrated that the initiation of slug flow can be understood by considering the stability of a stratified flow and the stability of slugs (137, 138, 164, 165, 172, 188). A mechanism for the transition between slug and plug flow has been defined (149). A comprehensive theoretical approach for flow regime transitions has been presented. These point to the need to improve our modeling of stratified flows (167, 221).

(e) Entrainment in annular flow is interpreted as representing a balance between the rate of atomization of the wall film and the rate of deposition of drops. Measurements of these two processes have been made (126, 139, 140, 143, 149, 163, 180, 185, 186, 191, 218, 219).

(f) Basic studies of suspension flow. One of the striking results of measurements of the deposition process in annular flows is the observed marked decrease in the deposition constant at relatively small concentrations. This has prompted extensive studies of dispersion and deposition (135, 153, 158, 159, 166, 169, 171, 203, 224, 226, 227, 229, 234, 235, 239, 240, 241). Measurements of droplet size have been made as an adjunct to these studies (199, 216, 220, 225).

(g) Stratified flow appears to be the simplest regime, yet it is poorly understood. This has prompted two studies (125, 178).

(h) The modeling a slug flow has been considered in several studies (174, 205, 232).

4. Personal

We are quite pleased with the progress that we have made under this grant. The work has been recognized by others. As mentioned in Section 1, the principal investigator was the first winner of the International Prize on Multiphase Flow in 1998. He was recognized, both for his contributions in turbulence and for his leadership in developing a scientific approach to multiphase flows, by being elected to the American Academy of Arts and Sciences in 1997 and to the National Academy of Sciences in 1999.

The story has not been completed with the work done under this grant. However, the recent results from our laboratory, as well as other laboratories, indicate that the scientific community is well on the way to developing multiphase flow as separate scientific discipline. This is documented in the recent (2002) DOE Workshop held at the University of Illinois to Define Scientific Issues in Multiphase Flow.

These events have motivated the present effort by the Principal Investigator to develop a book which defines this new field in a more precise way.

Publications

- (122) “Gas-Liquid Flow in Pipelines,” *Physico Chemical Hydrodynamics*, **9**, 101-114 (1987).
- (123) With P. Y. Lin, “Detection of Slug-Flow from Pressure Measurements,” *Int. J. Multiphase Flow*, **13**, 13-21 (1987).
- (125) With N. Andritsos, “Interfacial Instabilities for Horizontal Gas-Liquid Flows in Pipelines,” *Int. J. Multiphase Flow*, **13**, 583-603 (1987).
- (126) With M. M. Lee, “The Inhibition of Droplet Deposition by the Presence of a Liquid Wall Film,” *Int. J. Multiphase Flow*, **14**, 129-140 (1988).
- (131) With V. Bontozoglou, “Effects of Finite Depth and Current Velocity on Large Amplitude Kelvin-Helmholtz Waves,” *J. Fluid Mechanics*, **196**, 187-204 (1988).
- (135) With M. M. Lee and R. J. Adrian, “An Axial Viewing Photographic Technique to Study Turbulence Characteristics of Particles,” *Int. J. Multiphase Flow*, **15**, 787-802 (1989).
- (136) With V. Bontozoglou, “Wave Height Estimation in Stratified Gas-Liquid Flows,” *A.I.Ch.E. Journal*, **35**, 1346-1350 (1989).
- (137) With N. Andritsos and L. Williams, “Effect of Liquid Viscosity on the Stratified-Slug Transition in Horizontal Pipe Flow,” *Int. J. Multiphase Flow*, **2**, 877-89 (1989).
- (138) With Z. Ruder and P. J. Hanratty, “Necessary Conditions for the Existence of Slugs,” *Int. J. Multiphase Flow*, **15**, 209-226 (1989).
- (139) With S. A. Schadel, “Interpretation of Atomization Rates of the Liquid Film in Gas-Liquid Annular Flow,” *Int. J. Multiphase Flow*, **15**, 893-900 (1989).
- (140) With M. M. Lee and R. J. Adrian, “The Interpretation of Droplet Deposition Measurements with a Diffusion Model,” *Int. J. Multiphase Flow*, **15**, 459-469 (1989).
- (142) With Z. Ruder, “A Definition of Gas-Liquid Plug Flow in Horizontal Pipes,” *Int. J. Multiphase Flow*, **16**, 233-242 (1990).
- (143) S. A. Schadel, G. W. Leman and J. L. Binder, “Rate of Atomization and Deposition in Vertical, Annular Flow,” *Int. J. Multiphase Flow*, **16**, 363-374 (1990).
- (145) With V. Bontozoglou, “Capillary-Gravity Kelvin-Helmholtz Waves Close to Resonance,” *J. Fluid Mechanics*, **217**, 71-91 (1990).

- (148) "Effect of Gas Flow on Physical Absorption," published in *Gas Transfer at Water Surfaces*, J. Gulliver et al (eds), ASCE NY, NY (1991).
- (149) With J. Binder, "A Diffusion Model for Droplet Deposition in Gas/Liquid Annular Flow," *Int. J. Multiphase Flow*, **17**, 1-11 (1991).
- (153) With R. Mei and R. L. Adrian, "Particle Dispersion in Isotropic Turbulence and Stokes Drag and Basset Force with Gravitational Settling," *J. Fluid Mechanics*, **225**, 481-495 (1991).
- (158) With J. B. Young, "Trapping of Solid Particles at a Wall in a Turbulent Flow," *A.I.Ch.E. Journal*, **37**, 1529-1536 (1991).
- (159) With J. B. Young, "Optical Studies of Turbulent Motion of Solid Particles in a Pipe Flow," *J. Fluid Mechanics*, **231**, 665-688 (1991)
- (161) With L. M. Wolff and Z. C. Liu, "A Fluorescence Technique to Measure Concentration Gradients Near an Interface," published in *Gas Transfer at Water Surfaces*, J. Gulliver et al (eds), ASCE, New York, NY (1991).
- (162) "Effect of Gas Flow on Physical Absorption," published in *Gas Transfer at Water Surfaces*, J. Gulliver, et al (eds.), ASCE, New York (1991).
- (163) With J. W. Brooke, K. Kontomaris, and J. B. McLaughlin, "Turbulent Deposition and Trapping of Aerosols at a Wall," *Phys. of Fluids A*, **4**, 825-833 (1992).
- (164) With N. Andritsos and V. Bontozoglou, "Transition to Slug Flow in Horizontal Pipes," *Chemical Engineering Communications*, **118**, 361-385 (1992).
- (165) With Z. Fan, "A Model for Stationary Slugs," *Int. J. of Multiphase Flow*, **18**, 477-494 (1992).
- (166) With K. Kontomaris and J. B. McLaughlin, "An Algorithm for Tracking Fluid Particles in a Spectral Simulation of Turbulent Channel Flow," *J. Computational Physics*, **103**, 231-242 (1992).
- (167) With J. L. Binder, "Use of Lagrangian Methods to Describe Drops Deposition and Distribution in Horizontal Gas-Liquid Annular-Flow," *Int. J. of Multiphase Flow*, **18**, 803-820 (1992).
- (169) "Use of Lagrangian Statistics to Describe Turbulent Dispersed Fows," *Particulate Two-Phase Flow*, ed. M. Roco, Butterworth Heinemann, Stoneham, Massachusetts, 1993.

- (170) With J. C. Asali, "Ripples Generated on a Liquid Film at High Gas Velocities," *Int. J. Multiphase Flow*, **19**, 229-243 (1993).
- (171) With J. L. Binder, "Use of Lagrangian Statistics to Describe Slurry Transport," *A.I.Ch.E. Journal*, **39**, 1581-1589 (1993).
- (172) With Z. Fan and F. Lusseyran, "Initiation of Slugs in Horizontal Gas-Liquid Flows," *A.I.Ch.E. Journal*, **31**, 1741-1753 (1993).
- (174) With Z. Fan and Z. Ruder, "Pressure Profiles for Slugs in Horizontal Pipelines," *Int. J. Multiphase Flow*, **19**, 421-437 (1993).
- (176) With L. M. Wolff, "Instantaneous Concentration Profiles of Oxygen Accompanying Absorption in a Stratified Flow," *Exp. in Fluids*, **16**, 385-392 (1994).
- (178) With L. Dykhno and L. R. Williams, "Maps of Mean Gas Velocity for Stratified Flows With and Without Atomization," *Int. J. Multiphase Flow*, **20**, 691-702 (1994).
- (180) With J. W. Brooke and J. B. McLaughlin, "Free-Flight Mixing and Deposition of Aerosols," *Phys. of Fluids*, **6**, 3404-15 (1994).
- (183) With S. R. Duke and L. M. Wolff, "Slopes of Small-Scale Wind Waves and Their Relation to Mass Transfer Rates," *Exp. in Fluids*, **19**, 280-292 (1995).
- (185) With L. R. Williams and L. A. Dykhno, "Droplet Flux Distributions and Entrainment in Horizontal Gas-Liquid Flows," *Int. J. Multiphase Flow*, **22**, 1-18 (1996).
- (186) With L. A. Dykhno, "Use of the Interchange Model to Predict Entrainment in Vertical Annular Flow," *Chem. Eng. Comm.*, **141**, 207-235 (1996).
- (188) With B. D. Woods, "Relation of Slug Stability to Shedding Rate," *Int. J. Multiphase Flow*, **22**, 809-828 (1996).
- (191) With K. J. Hay and Z. C. Liu, "Relation of Deposition to Drop Size When the Rate Law is Nonlinear," *Int. J. of Multiphase Flow*, **22**, 829-848 (1996).
- (193) With Mark J. McCready, "Phenomenological Understanding of Gas-Liquid Separated Flows," Volume 8, *Multiphase Science & Technology*, Begell House, Inc., New York, NY (1996)
- (199) With Hay, K. J. and Liu, Z. C., "A Backlighting Imaging Technique for Particle Size Measurements in Two-Phase Flow," *Exp. in Fluids*, **25**, 226-232 (1998).

- (202) With Woods, B. D., Iliopoulos, I., and Pan, L., "The Roles of Interfacial Stability and Particle Dynamics in Multiphase Flows: A Personal Viewpoint," *Int. J. Multiphase Flow*, **26**, 169-190 (1999).
- (203) With Iliopoulos, I., "Turbulent Dispersion in a Nonhomogeneous Field," *J. Fluid Mech.*, **392**, 45-71 (1999).
- (205) With Woods, B. D., "Influence of Froude Number on Physical Processes Determining Frequency of Slugging in Horizontal Gas-Liquid Flow," *Int. J. Multiphase Flow*, **25**, 1195-1223 (1999).
- (207) With Woods, B. D. and Hurlburt, E., "Mechanism of Slug Formation in Downwardly Inclined Pipes," *Int. J. Multiphase Flow*, **26**, 977-998 (2000).
- (210) With Simmons, M.J.H., "Transition from Stratified to Intermittent Flows in Small Angle Upflows," *Int. J. Multiphase Flow*, **27**, 519-616 (2001).
- (212) With Al-Sarkhi, A., "Effect of Drag-Reducing Polymers on Annular Gas-Liquid Flow in a Horizontal Pipe," *Int. J. Multiphase Flow*, **27**, 1151-1162 (2001).
- (215) With Al-Sarkhi, "Effect of Pipe Diameter on the Performance of Drag-Reducing Polymers in Annular Gas-Liquid Flows," *Trans. I. Chem. E.*, **79**, Part A, 402-408 (2001).
- (216) With Simmons, Mark J. H., "Droplet Size Measurements in Horizontal Annular Gas-Liquid Flow," *Int. J. Multiphase Flow*, **27**, 861-883 (2001).
- (218) With Pan, L., "Correlation of Entrainment for Annular Flow in a Vertical Pipe," *Int. J. Multiphase Flow*, **28**, 363-384 (2002).
- (219) With Pan, L., "Correlation of Entrainment for Annular Flow in a Horizontal Pipe," *Int. J. Multiphase Flow*, **28**, 358-408 (2002).
- (220) With Hurlburt, E. T., "Measurement of Drop Size in Horizontal Annular Flow with the Immersion Technique," *Exp. Fluids*, **32**, 692-699 (2002).
- (221) With Hurlburt, E. T., "Theoretical Prediction of the Transition from Stratified to Slug and Plug Flow in Long Pipes," *Int. J. Multiphase Flow*, **28**, 707-729 (2002).
- (223) With Soleimani, Arash, Al-Sarkhi, Abdel, "Effect of Drag-Reducing Polymers on Interfacial Drag and Transition to Slug Flow," *Int. J. Multiphase Flow*, **28**, 1911-1927 (2002).

- (224) With Mito, Yoichi, "Use of a Modified Langevin Equation to Describe Turbulent Dispersion of Fluid Particles in a Channel Flow," *Turbulence and Combustion*, **68**, 1-26 (2002).
- (225) With Al-Sarkhi, A., "Effect of Pipe Diameter on the Drop Size in a Horizontal Annular Gas-Liquid Flow," *Int. J. Multiphase Flow*, **28**, 1617-1629 (2002).
- (226) With Mito, Yoichi, "Lagrangian Stochastic Simulation of Turbulence Dispersion of Heat Markers in a Channel Flow," *Int. J. Heat Mass Transfer*, **46**, 1063-1073 (2003).
- (227) With Baik, S., "Concentration Profiles and Prediction of the Transition from Stratified to Annular Flow in Horizontal Pipes," *Int. J. Multiphase Flow*, **29**, 329-338 (2003).
- (228) With Soleimani, Arash, "Critical Liquid Flows for the Transition from the Pseudo-Slug and Stratified Patterns to Slug Flow", *Int. J. Multiphase Flow*, **29**, 51-67 (2003).
- (229) With Iliopoulos, Ilias and Mito, Yoichi, "A Stochastic Model for Solid Particle Dispersion in a Nonhomogeneous Turbulent Flow", *Int. J. Multiphase Flow*, **29**, 375-394 (2003).
- (230) With Nakagawa, S., Na, Y., "Influence of a Wavy Boundary on Turbulence Part I: Highly Rough Surface", *Exp. Fluids*, **35**, 422-436 (2003).
- (231) With Nakagawa, S., "Influence of a Wavy Boundary on Turbulence Part II. Intermediate Roughened and Hydraulically Smooth Surfaces", *Exp. Fluids*, **35**, 437-447 (2003).
- (232) With Baik, Seunghyun, "Effects of a Drag Reducing Polymer on Stratified Gas-Liquid Flow in a Large Diameter Horizontal Pipe", *Int. J. Multiphase Flow*, **29**, 1749-1757 (2003).
- (234) With Mito, Yoichi, "A Stochastic Description of Wall Sources in a Turbulent Field. Part 1: Verification", *Int. J. Multiphase Flow*, **29**, 1373-1394 (2003).
- (235) With Iliopoulos, Ilias, Mito, Yoichi, "A Stochastic Model for Solid Particle Dispersion in a Nonhomogeneous Turbulent Field", *Int. J. Multiphase Flow*, **29**, 375-394 (2003).
- (236) Editor, "Workshop on Scientific Issues in Multiphase Flow", *Int. J. Multiphase Flow*, **29**, 1041-1146 (2003).
- (237) With Theofanous, Theo. G., "Report of Study Group on Flow Regimes in Multifluid Flow", *Int. J. Multiphase Flow*, **29**, 1061-1068 (2003).

- (239) With Mito, Y., "Stochastic Description of Wall Sources in a Turbulent Field: Part 2. Calculation for a Simplified Model of Horizontal Annular Flows," *Int. J. Multi-phase Flow*, **30**, 803-825 (2004).
- (240) With Mito, Y., "Concentration Profiles in a Turbulent Suspension When Gravity Is Not Affecting Deposition," *Int. J. Multiphase Flow*, accepted.
- (241) With Mito, Y., "Stochastic Description of Wall Sources in a Turbulent Field. Part 3: Effect of Gravitational Settling on the Concentration Profiles," *Int. J. Multiphase Flow*, accepted.
- (243) "Fully-Developed Gas-Liquid Flows," to appear in *Multiphase Science and Technology* (2004).
- (244) "Microphysics of Multiphase Flows," to appear in *Multiphase Science and Technology* (2004).