Characterization of foam flow in pipes using two flow regime concept

Rahul Narayanrao Gajbhiye

Louisiana State University and Agricultural and Mechanical College

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_dissertations

Part of the Petroleum Engineering Commons

Recommended Citation


https://digitalcommons.lsu.edu/gradschool_dissertations/2369

This Dissertation is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Doctoral Dissertations by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
CHARACTERIZATION OF FOAM FLOW IN PIPES
USING TWO FLOW REGIME CONCEPT

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
Requirements for the degree of
Doctor of Philosophy

in

The Department of Petroleum Engineering

by

Rahul Gajbhiye
B.E., Pune University, 1999
MCA, Amravati University, 2003
August 2011
ACKNOWLEDGEMENTS

I am very grateful to Craft and Hawkins Department of Petroleum Engineering for its financial support without which this research wouldn’t have crafted into a dissertation. I would like to express special thanks to Chevron Inc., Rural Research Institute, and Keller professorship for the financial support. Additional appreciation is reserved for our industry partners, especially Stepan and Baker Petrolite, who provided the surfactant samples.

I would especially like to thank my advisor Dr. Seung Ihl Kam who has been very patient and encouraging to take that one extra step. His insight into this topic, organization skills and dedication to research always been inspiring to me. He has always been on my side and sailed me through the tough times. This dissertation evolved from the numerous discussions we had which I would always look forward to.

I am also indebted to my committee members Dr. Andrew Wojtanowicz, Dr. Dandina Rao, Dr. Richard Hughes, and Dr. Mayank Tyagi for their expertise and valuable suggestions. I would like to show my gratitude towards the staff at LSU petroleum engineering, especially Darryl Bourgoyne, Gerry Masterman, and Fenelon Nunes, for their hard work and hours spent in setting up the laboratory equipment. Heartfelt thanks to my colleagues for the many enlightening conversations and my friends at LSU who made this journey of four years very pleasant and memorable.

I am forever thankful to my parents who have always believed that education is above all and their values have helped pave the path of privileged education. My deepest gratitude to my brothers, sisters and relatives for their unconditional love and support throughout these four years.
TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................... ii

LIST OF TABLES ...................................................................................................................... v

LIST OF FIGURES .................................................................................................................. vi

ABSTRACT .............................................................................................................................. xvi

1. INTRODUCTION ............................................................................................................... 1
  1.1 Background .................................................................................................................... 1
  1.2 Objective of This Study ................................................................................................. 2
  1.3 Chapter Description ....................................................................................................... 4

2. LITERATURE REVIEW .................................................................................................... 6
  2.1 Foams in General .......................................................................................................... 6
  2.2 Foam Flow in Pipe and Annuli ...................................................................................... 7
  2.3 Effect of Inclination on Bulk Foam Rheology .............................................................. 11

3. METHODS AND MATERIALS ........................................................................................ 14
  3.1 Experimental Set-up and Materials ............................................................................. 14
  3.2 Procedure ..................................................................................................................... 16
  3.3 Data Analysis ................................................................................................................ 18

4. RESULTS AND DISCUSSIONS: FOAM FLOW IN HORIZONTAL PIPE .................... 20
  4.1 Experiments in Stainless-Steel Pipes (0.36/0.5 inch ID/OD): Base Case and Cases 1- 4 .......................................................... 22
    4.1.1 Base Case ............................................................................................................. 22
    4.1.2 Effect of Surfactant Concentrations (Case 1 and Case 2) .................................. 32
    4.1.3 Effect of Surfactant Formulations (Case 3 and Case 4) .................................... 38
  4.2 Experiments in Transparent Nylon Pipes (0.38 inch ID and 0.5 inch OD):
    Cases 5 through 8 ........................................................................................................... 43
    4.2.1 Flow Experiments with FA-406 (Case 5) ............................................................ 43
    4.2.2 Flow Experiments with Aquet-944 surfactants (Case 6, Case 7, and Case 8) ........ 43
  4.3 Visual Observations from Nylon-Pipe Experiments (0.38 inch ID and 0.5 inch OD) .......................................................... 52

5. RESULTS AND DISCUSSIONS: FOAM FLOW IN INCLINED PIPE ...................... 64
  5.1 Base Case (Inclination 0°) ........................................................................................... 64
  5.2 Effect of Inclination on Two Flow Regimes (Case 1-Case 4) ..................................... 69
  5.3 Transition from Segregated to Plug Flow Pattern (Case 5) ........................................ 72
  5.4 Implication of Results to Pressure Contours at Different Inclination Angles .......... 76
LIST OF TABLES

TABLE 4.1 Density and Surface Tension of Surfactant Samples……………………………… 20
TABLE 4.2 Nine Different Cases Examined for Foam Flow in Horizontal Pipe……………… 21
TABLE 4.3 Comparison of Surfactant Characteristics.................................................. 22
TABLE 5.1 List of the Six Cases at Different Inclination Angle ...................................... 64
TABLE 6.1 Input Data for the Hydraulic Calculation Along the Annulus...................... 89
## LIST OF FIGURES

1.1 Steady-state pressure contours showing two flow regimes for foam flow in pipe. 3

2.1 A schematic showing changes in apparent foam viscosity ($\mu_{\text{app}}$) as a function of foam quality at fixed total injection velocity. ......................................................... 9

3.1 Experimental set-up for foam flow in horizontal pipe. ........................................ 15

3.2 Laboratory set-up for flow experiments in different inclination angles. .......... 17

4.1 Shape of the droplet for the surface tension measurement using pendent drop method (Surfactant concentration 0.1 weight % for a) Cedepal FA-406, b) Stepanform-1050, and c) Aquet-944). ................................................. 21

4.2 Shape of the droplet for the surface tension measurement using pendent drop method (Surfactant concentration 0.5 weight % for a) Cedepal FA-406, b) Stepanform-1050, and c) Aquet-944). ................................................. 21

4.3(a) Pressure response of Base Case (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 20 cm$^3$/min. ......................................................... 23

4.3(b) Pressure response of Base Case (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 40 cm$^3$/min. ......................................................... 24

4.3(c) Pressure response of Base Case (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 60 cm$^3$/min. ......................................................... 24

4.3(d) Pressure response of Base Case (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 80 cm$^3$/min. ......................................................... 25

4.4(a) Base Case pressure response as a function of distance (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at $u_w = 0.033$ ft/s (or $Q_w = 40$ cm$^3$/s). ...... 26

4.4(b) Base Case pressure response as a function of distance (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at $u_w = 0.033$ ft/s (or $Q_w = 40$ cm$^3$/s). ...... 27

4.5(a) Base Case pressure response as a function of gas velocity at four different liquid velocities (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). ................. 28

4.5(b) Base Case pressure response as a function of foam quality at four different liquid velocities (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). ................. 28

4.6(a) Base Case shear stress as a function of shear rate at four different liquid velocities (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). ................. 29
4.6(b) Base Case foam viscosity as a function of foam quality and shear rate at four different liquid velocities (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). ................................................................. 29

4.7(a) Pressure contours of the Base Case with liquid velocity on x axis and gas velocity on y axis (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state pressure drop in [psi]. ...................... 31

4.7(b) Apparent viscosity contours of Base Case with liquid velocity on x axis and gas velocity on y axis (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state apparent foam viscosity in [cp]. ........... 31

4.8(a) Pressure response of Case 1 as a function of foam quality at four different liquid velocities (0.1 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). ......................... 33

4.8(b) Foam viscosity of Case 1 as a function of foam quality and shear rate at four different liquid velocities (0.1 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). ................................................................. 33

4.9(a) Pressure contours of Case 1 with liquid velocity on x axis and gas velocity on y axis (0.1 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state pressure drop in [psi]. .............................................. 34

4.9(b) Apparent viscosity contours of Case 1 with liquid velocity on x axis and gas velocity on y axis (0.1 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state apparent foam viscosity in [cp]. .......... 34

4.10(a) Pressure response of Case 2 as a function of foam quality at four different liquid velocities (5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). ......................... 36

4.10(b) Apparent viscosity of Case 2 as a function of foam quality and shear rate at four different liquid velocities (5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). .......................... 36

4.11(a) Pressure contours of Case 2 with liquid velocity on x axis and gas velocity on y axis (5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state pressure drop in [psi]. .............................................. 37

4.11(b) Apparent viscosity contours of Case 2 with liquid velocity on x axis and gas velocity on y axis (5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state apparent foam viscosity in [cp]. .............. 37

4.12(a) Pressure response of Case 3 as a function of foam quality at four different liquid velocities (0.5 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe). .... 39
4.12(b) Foam viscosity of Case 3 as a function of foam quality and shear rate at four different liquid velocities (0.5 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe). ................................................................. 39

4.13(a) Pressure response of Case 4 as a function of foam quality at four different liquid velocities (0.1 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe). .... 40

4.13(b) Foam viscosity of Case 4 as a function of foam quality and shear rate at four different liquid velocities (0.1 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe). .............................................................................. 40

4.14(a) Pressure contours of Case 3 with liquid velocity on x axis and gas velocity on y axis (0.5 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state pressure drop in [psi]. .............................................. 41

4.14(b) Apparent viscosity contours of Case 3 with liquid velocity on x axis and gas velocity on y axis (0.5 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state apparent foam viscosity in [cp]. 41

4.15(a) Pressure contours of Case 4 with liquid velocity on x axis and gas velocity on y axis (0.1 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state pressure drop in [psi]. .............................................. 42

4.15(b) Apparent viscosity contours of Case 4 with liquid velocity on x axis and gas velocity on y axis (0.1 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state apparent foam viscosity in [cp]. 42

4.16(a) Pressure response of Case 5 as a function of foam quality at four different liquid velocities (0.5 wt% FA-406, 0.38/0.5” ID/OD nylon pipe). ............................................. 44

4.16(b) Foam viscosity of Case 5 as a function of foam quality and shear rate at four different liquid velocities (0.5 wt% FA-406, 0.38/0.5” ID/OD nylon pipe) ................................ 44

4.17(a) Pressure contours of Case 5 with liquid velocity on x axis and gas velocity on y axis (0.5 wt% FA-406, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state pressure drop in [psi]. ................................................................. 45

4.17(b) Apparent viscosity contours of Case 5 with liquid velocity on x axis and gas velocity on y axis (0.5 wt% FA-406, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state apparent foam viscosity in [cp]. ......................... 45

4.18(a) Pressure response of Case 6 as a function of foam quality at four different liquid velocities (5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe). ............................................. 46

4.18(b) Foam viscosity of Case 6 as a function of foam quality and shear rate at four different liquid velocities (5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe) ........... 46
4.19(a) Pressure contours of Case 6 with liquid velocity on x axis and gas velocity on y axis (5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state pressure drop in [psi]…………………………………………….. 47

4.19(b) Apparent viscosity contours of Case 6 with liquid velocity on x axis and gas velocity on y axis (5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state apparent foam viscosity in [cp]………………………………… 47

4.20(a) Pressure response of Case 7 as a function of foam quality at four different liquid velocities (0.5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe)…………………………………………….. 48

4.20(b) Foam viscosity of Case 7 as a function of foam quality and shear rate at four different liquid velocities (0.5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe)…..………… 48

4.21(a) Pressure contours of Case 7 with liquid velocity on x axis and gas velocity on y axis (0.5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state pressure drop in [psi]…………………………………………….. 49

4.21(b) Apparent viscosity contours of Case 7 with liquid velocity on x axis and gas velocity on y axis (0.5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state apparent foam viscosity in [cp]………………………………… 49

4.22(a) Pressure response of Case 8 as a function of foam quality at four different liquid velocities (0.1 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe)…………………………………………….. 50

4.22(b) Foam viscosity of Case 8 as a function of foam quality and shear rate at four different liquid velocities (0.1 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe)…..………… 50

4.23(a) Pressure contours of Case 8 with liquid velocity on x axis and gas velocity on y axis (0.1 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state pressure drop in [psi]…………………………………………….. 51

4.23(b) Apparent viscosity contours of Case 8 with liquid velocity on x axis and gas velocity on y axis (0.1 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state apparent foam viscosity in [cp]………………………………… 51

4.24 Results from Case 5 visualization analysis near the outlet (i.e., about 1 ft upstream from the outlet) for 0.5 wt% FA-406 surfactant in a wide range of gas and liquid velocities. …………………………………………………….. 53

4.25(a) Effect of gas and liquid injection velocities on the size of free gas in the high-quality regime. ………………………………………………………………………….. 54

4.25(b) Effect of gas and liquid injection velocities on the size of foam slugs in the high-quality regime. ………………………………………………………………………….. 55
4.26 Results from Case 7 visualization analysis near the outlet (i.e., about 1 ft upstream from the outlet) for 0.5 wt% Aquet-944 surfactant in a wide range of gas and liquid velocities. The overall response is similar to Fig. 4.24 with 0.5 wt% FA-406.  

4.27 Results from Case 8 visualization analysis near the outlet (i.e., about 1 ft upstream from the outlet) for 0.1 wt% Aquet-944 surfactant in a wide range of gas and liquid velocities.  

4.28 A schematic of characterization of foam flow in horizontal pipes based on foam texture, flow pattern, and pressure response.  

4.29(a) Effect of surfactant concentration by using 0.1, 0.5, and 5 wt% of Aquet-944 at the same liquid velocity of 0.015 ft/s ($Q_w = 20 \text{ cm}^3/\text{min}$).  

4.29(b) Effect of surfactant concentration by using 0.1, 0.5, and 5 wt% of Aquet-944 at the same liquid velocity of 0.030 ft/s ($Q_w = 40 \text{ cm}^3/\text{min}$).  

4.30 A schematic showing the implication of two-flow-regime on underbalanced drilling processes.  

5.1(a) Pressure response of the Base Case (Inclination 0°) at pressure ports A through H with liquid injection rate 20 cm$^3$/min.  

5.1(b) Pressure response of the Base Case (Inclination 0°) at pressure ports A through H with liquid injection rate 40 cm$^3$/min.  

5.1(c) Pressure response of the Base Case (Inclination 0°) at pressure ports A through H with liquid injection rate 60 cm$^3$/min.  

5.1(d) Pressure response of the Base Case (Inclination 0°) at pressure ports A through H with liquid injection rate 80 cm$^3$/min.  

5.2 The steady-state pressure drops over 8.52 ft. pipe length at various gas rates, or the steady-state shear stress at various shear rates at fixed liquid velocity (Base case with inclination angle 0°).  

5.3 The steady-state pressure drops over 8.52 ft. pipe length at various foam qualities or apparent foam viscosity at various shear rates (Base case with inclination angle 0°).  

5.4 Pressure and apparent-viscosity contours for Base Case: (a) pressure values in psi over 8.52 ft length and (b) apparent-viscosity in cp calculated from pressure data.
5.5 Pressure and apparent-viscosity contours for Case 1 (Inclination 45° Upward): (a) pressure values in psi over 8.52 ft. length and (b) apparent-viscosity in cp calculated from pressure data. ................................................................. 70

5.6 Pressure and apparent-viscosity contours for Case 2 (Inclination 90° Upward): (a) pressure values in psi over 8.52 ft. length and (b) apparent-viscosity in cp calculated from pressure data. ................................................................. 70

5.7 Pressure and apparent-viscosity contours for Case 3 (Inclination 45° Downward): (a) pressure values in psi over 8.52 ft. length and (b) apparent-viscosity in cp calculated from pressure data. ................................................................. 71

5.8 Pressure and apparent-viscosity contours for Case 4 (Inclination 90° Downward): (a) pressure values in psi over 8.52 ft. length and (b) apparent-viscosity in cp calculated from pressure data. ................................................................. 71

5.9 Flow patterns observed in Base Case (Inclination 0°). ........................................... 73

5.10 Flow patterns observed in Case 1 (Inclination 45° Upward). ................................. 74

5.11 Flow patterns observed in Case 3 (Inclination 45° Downward). ............................ 74

5.12 Boundaries separating three different patterns: the transition from segregated to plug flow is significantly affected by inclination angles. ................................................ 75

5.13 A schematic showing the transition from segregated flow to plug flow at different inclination angles. ................................................................. 77

6.1 Beyer et al.’s model: (a) foam viscosity vs. foam quality and (b) viscosity contours. ................................................................. 80

6.2 Sanghani and Ikoku’s model: (a) foam viscosity vs. foam quality and (b) viscosity contours. ................................................................. 81

6.3 Reidenbach et al.’s model: (a) foam viscosity vs. foam quality and (b) viscosity contours. ................................................................. 82

6.4 Pressure contour map developed using Sanghani and Ikoku data. ....................... 83

6.5 Pressure contour map developed using Briceno and Joseph data. ....................... 84

6.6 Pressure contour map developed using Guzman et al.’s data. ....................... 85

6.7 Comparison with Taitel and Dukler’s flow regime map (1976): (a) range of experimental conditions of this study and (b) location of data points from contour map in Fig. 4.7(a). ................................................................. 86
6.8 Comparison with Baker’s flow regime map (1954): (a) range of experimental conditions of this study and (b) location of data points from contour map in Fig. 4.7(a). ................................................................. 87

6.9 Comparison with Beggs and Brill’s flow regime map (1973): (a) range of experimental conditions of this study and (b) location of data points from contour map in Fig. 4.7(a). ................................................................. 88

6.10 Apparent foam viscosity as function of foam quality for Case 4 Stepanform-1050, 0.1 wt% concentration: (a) low-quality regime and (b) high-quality regime. ................................................................. 91

6.11 Results of example foam drilling hydraulics calculations: (a) pressure (b) foam quality (c) foam viscosity (d) total velocity (e) hydrostatic pressure gradient, and (f) frictional pressure gradient. ................................................................. 94

6.12 Statistical analysis of Base Case (0.5 wt% FA-406) experiments. ...................... 95

6.13 Statistical analysis of Case 1 (0.1 wt% FA-406) experiments. ......................... 96

6.14 Statistical analysis of Case 2 (5.0 wt% FA-406) experiments. ......................... 96

A1(a) Pressure response of Case1 (0.1 wt% FA-406, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 20 cm³/min. ................................................................. 108

A1(b) Pressure response of Case1 (0.1 wt% FA-406, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 40 cm³/min. ................................................................. 109

A1(c) Pressure response of Case1 (0.1 wt% FA-406, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 60 cm³/min. ................................................................. 109

A1(d) Pressure response of Case1 (0.1 wt% FA-406, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 80 cm³/min. ................................................................. 110

A2(a) Pressure response of Case2 (5.0 wt% FA-406, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 20 cm³/min. ................................................................. 110

A2(b) Pressure response of Case2 (5.0 wt% FA-406, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 40 cm³/min. ................................................................. 111

A2(c) Pressure response of Case2 (5.0 wt% FA-406, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 60 cm³/min. ................................................................. 111

A2(d) Pressure response of Case2 (5.0 wt% FA-406, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 80 cm³/min. ................................................................. 112
B1(a) Pressure response of Case3 (0.5 wt% Stepanform1050, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 20 cm³/min. .......................... 113

B1(b) Pressure response of Case3 (0.5 wt% Stepanform1050, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 40 cm³/min. .......................... 114

B1(c) Pressure response of Case3 (0.5 wt% Stepanform1050, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 60 cm³/min. .......................... 114

B1(d) Pressure response of Case3 (0.5 wt% Stepanform1050, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 80 cm³/min. .......................... 115

B2(a) Pressure response of Case4 (0.1 wt% Stepanform1050, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 20 cm³/min. .......................... 115

B2(b) Pressure response of Case4 (0.1 wt% Stepanform1050, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 40 cm³/min. .......................... 116

B2(c) Pressure response of Case4 (0.1 wt% Stepanform1050, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 60 cm³/min. .......................... 116

B2(d) Pressure response of Case4 (0.1 wt% Stepanform1050, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 80 cm³/min. .......................... 117

C1(a) Pressure response of Case5 (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 20 cm³/min. .................................................. 118

C1(b) Pressure response of Case5 (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 40 cm³/min. .................................................. 119

C1(c) Pressure response of Case5 (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 60 cm³/min. .................................................. 119

C1(d) Pressure response of Case5 (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 80 cm³/min. .................................................. 120

C2(a) Pressure response of Case6 (5.0 wt% Aquet-944, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 20 cm³/min. .................................................. 120

C2(b) Pressure response of Case6 (5.0 wt% Aquet-944, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 40 cm³/min. .................................................. 121

C2(c) Pressure response of Case6 (5.0 wt% Aquet-944, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 60 cm³/min. .................................................. 121
C2(d) Pressure response of Case 6 (5.0 wt% Aquet-944, 0.38/0.5” ID/OD Nylon6 pipe) at fixed liquid injection rate of 80 cm³/min. .............................................................. 122

C3(a) Pressure response of Case 7 (0.5 wt% Aquet-944, 0.38/0.5” ID/OD Nylon6 pipe) at fixed liquid injection rate of 20 cm³/min. .............................................................. 122

C3(b) Pressure response of Case 7 (0.5 wt% Aquet-944, 0.38/0.5” ID/OD Nylon6 pipe) at fixed liquid injection rate of 40 cm³/min. .............................................................. 123

C3(c) Pressure response of Case 7 (0.5 wt% Aquet-944, 0.38/0.5” ID/OD Nylon6 pipe) at fixed liquid injection rate of 60 cm³/min. .............................................................. 123

C3(d) Pressure response of Case 7 (0.5 wt% Aquet-944, 0.38/0.5” ID/OD Nylon6 pipe) at fixed liquid injection rate of 80 cm³/min. .............................................................. 124

C4(a) Pressure response of Case 8 (0.1 wt% Aquet-944, 0.38/0.5” ID/OD Nylon6 pipe) at fixed liquid injection rate of 20 cm³/min. .............................................................. 124

C4(b) Pressure response of Case 8 (0.1 wt% Aquet-944, 0.38/0.5” ID/OD Nylon6 pipe) at fixed liquid injection rate of 40 cm³/min. .............................................................. 125

C4(c) Pressure response of Case 8 (0.1 wt% Aquet-944, 0.38/0.5” ID/OD Nylon6 pipe) at fixed liquid injection rate of 60 cm³/min. .............................................................. 125

C4(d) Pressure response of Case 8 (0.1 wt% Aquet-944, 0.38/0.5” ID/OD Nylon6 pipe) at fixed liquid injection rate of 80 cm³/min. .............................................................. 126

D1(a) Pressure response of Case 1 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5” ID/OD Nylon 6 pipe) at fixed liquid injection rate of 20 cm³/min. ........ 127

D1(b) Pressure response of Case 1 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5” ID/OD Nylon 6 pipe) at fixed liquid injection rate of 40 cm³/min. ........ 128

D1(c) Pressure response of Case 1 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5” ID/OD Nylon 6 pipe) at fixed liquid injection rate of 60 cm³/min. ........ 128

D1(d) Pressure response of Case 1 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5” ID/OD Nylon 6 pipe) at fixed liquid injection rate of 80 cm³/min. ........ 129

D2(a) Pressure response of Case 2 (Inclination 90° Upward) (0.5 wt% FA-406, 0.38/0.5” ID/OD Nylon 6 pipe) at fixed liquid injection rate of 20 cm³/min. ........ 129

D2(b) Pressure response of Case 2 (Inclination 90° Upward) (0.5 wt% FA-406, 0.38/0.5” ID/OD Nylon 6 pipe) at fixed liquid injection rate of 40 cm³/min. ........ 130

D2(c) Pressure response of Case 2 (Inclination 90° Upward) (0.5 wt% FA-406, 0.38/0.5” ID/OD Nylon 6 pipe) at fixed liquid injection rate of 60 cm³/min. ........ 130
D2(d) Pressure response of Case 2 (Inclination 90° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 80 cm³/min. …… 131

D3(a) Pressure response of Case 3 (Inclination 45° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 20 cm³/min. …… 131

D3(b) Pressure response of Case 3 (Inclination 45° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 40 cm³/min. …… 132

D3(c) Pressure response of Case 3 (Inclination 45° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 60 cm³/min. …… 132

D3(d) Pressure response of Case 3 (Inclination 45° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 80 cm³/min. …… 133

D4(a) Pressure response of Case 4 (Inclination 90° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 20 cm³/min. …… 133

D4(b) Pressure response of Case 4 (Inclination 90° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 40 cm³/min. …… 134

D4(c) Pressure response of Case 4 (Inclination 90° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 60 cm³/min. …… 134

D4(d) Pressure response of Case 4 (Inclination 90° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 80 cm³/min. …… 134

D5(a) Pressure response of Case 5 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 10 cm³/min. …… 135

D5(b) Pressure response of Case 5 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 20 cm³/min. …… 135

D5(c) Pressure response of Case 5 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 40 cm³/min. …… 136

D5(d) Pressure response of Case 5 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 60 cm³/min. …… 136

D5(e) Pressure response of Case 5 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 80 cm³/min. …… 137
ABSTRACT

The objective of this study is to investigate the characteristics of foam flow behavior in pipes in a wide range of experimental conditions, including two pipe materials (stainless steel and nylon pipes with about 0.36 - 0.38 inch in inner diameter and 12 ft in length), three surfactant formulations (Cedepal FA-406, Stepanform-1050, and Aquet-944), and three surfactant concentrations (0.1, 0.5, and 5 wt%). The concept of “two foam-flow regimes”, consisting of high-quality regime and low-quality regime, is at the heart of interpreting the experimental data.

The experimental results in horizontal pipes showed the presence of two distinct high-quality and low-quality foam-flow regimes which could be identified by both pressure responses and direct visual observations. The high-quality regime was characterized by unstable and oscillating pressure responses represented by slug flow, while the low-quality regime was characterized by stable pressure responses represented by either plug flow or segregated flow. These two distinct flow regimes, separated by a locus of \( f_g^* \) in the contour plot, were shown to have different sensitivities to the change in gas and liquid velocities: (1) foam rheology in the high-quality regime was sensitive to both gas and liquid velocities because of the resulting changes in lengths of foam-slug and free-gas sections adjusted to the new flow conditions, and (2) foam rheology in the low-quality regime was sensitive to gas velocity because of finer foam texture at higher shear rates, and was relatively insensitive to liquid velocity because of lubricating effect and drainage effect.

The results at different inclination angles showed that foam rheology was not significantly altered by the inclination angle as long as the slug-flow or plug-flow pattern was
formed because of a viscous-force dominant environment. However, if flow conditions fell within the segregated-flow pattern, foam rheology was governed by the gravitational force rather than the viscous force, and therefore the flow characteristics were sensitive to inclination angles. These findings were supported by visual observations as well as pressure responses.

The implication of these experimental findings is discussed for applications such as foam-assisted underbalanced drilling processes and foam-fracturing treatments in the petroleum industry.
CHAPTER 1

INTRODUCTION

This chapter describes the background of this study followed by research objectives and chapter descriptions.

1.1 Background

The term, “foam”, in this study is defined as a dispersion of gas bubbles in a surfactant-laden bulk liquid phase. The gas phase typically forms a discontinuous phase within a continuous liquid phase with surfactant molecules. Other terms such as foam dispersion, polyaphron, and foamulsion are also used in the literature. Foam differs from other colloidal dispersions such as emulsions, as it can sustain a fairly high fraction of the internal phase (e.g. in excess of more than 74% of gas fraction) without turning into mist (Heller and Kuntamukkula, 1987). This characteristic often makes foams advantageous in many industrial engineering applications because of its low density, high viscosity, and high yield stress.

Previous experimental and theoretical studies find foam flow in pipe very challenging, which is primarily because foams exhibit nonlinear, non-Newtonian, visco-elastic behavior with striking meta-stability (Weaire and Phelan, 1996; Siegel and Vollhardt, 1996; Bergeron, 1997; Exerowa and Kruglyakov, 1998). One of the key parameters to understand foam behavior is bubble size, commonly referred to as foam texture. Foam flow experiments often encounter difficulties in measuring or reliably estimating bubble sizes and bubble-size distributions during the flow of interest, and describing foam rheology.

Foam is thermodynamically unstable and thus tends to minimize surface area by reducing free energy (Pugh, 1996; Rossen, 2004; Tadros, 2005). The presence of surfactant molecules
endows foams with a certain level of stability so that foams could be long-lived. How long foams can survive depends on the types of surfactant (i.e., formulation and concentration) and the related physicochemical mechanisms within the thin foam films, so called lamellae. Instability at those thin foam films leads to film rupture and bubble coalescence, eventually separating the gas phase from the bulk liquid phase. During the shear flow of foams in pipes, bubbles are constantly generated due to high shear stress and coalesced due to mechanical disturbance and gravity drainage, which also affects the distribution pattern of bubbles in the flow conduit. This is why understanding foam rheology in pipe cannot be achieved without characterizing foam flow behaviors.

Recently Bogdanovic et al. (2009) conducted foam-flow experiments in 0.5- and 1-inch diameter pipes by using five different types of surfactants, and proposed a new way to report and represent foam rheology by plotting the contours of resulting steady-state pressure drops as a function of both liquid and gas velocities on the x and y axes as shown in Fig. 1.1. The contour plots exhibited two distinct regimes, so-called “high-quality regime” and “low-quality regimes”, separated by a threshold foam quality denoted by $f_{\text{g}}^*$. They conjectured that these two distinct flow regimes based on the pressure measurements resulted from different foam flow patterns (i.e., bubble size and bubble-size distribution) which are sensitive to injection foam quality and total injection velocity.

1.2 Objective of This Study

In continuation with Bogdanovic et al. (2009), the major goal of this study is to characterize foam rheology in pipe based on pressure response and visual analysis of bubble size and bubble-size distribution.
Figure 1.1: Steady-state pressure contours showing two flow regimes for foam flow in pipe (Bogdanovic et al. 2009)

The first step of this study is to provide the characteristics of foam flow in horizontal direction in a manner consistent with the pressure response observed in both high-quality regime and low-quality regime, reflecting bubble-to-bubble and bubble-to-wall interactions.

In the second step, the experiments are extended to a wide range of inclination angles, all the way from vertical upward to vertical downward flow with inclined upward/downward and horizontal flows in between. These experiments make it possible to evaluate how foam rheology is affected in different flow directions comprehensively when other experimental conditions are kept identical. The concept of “two flow regimes” is applied to the interpretation of experimental results.
1.3 Chapter Description

The content of each chapter is summarized as follows:

Chapter 1 gives a brief introduction to this study followed by the objectives.

Chapter 2 provides fundamental concepts associated with foams and foam flow in pipes. It also includes previous research studies attributed to this subject with a special emphasis on foam rheology.

Chapter 3 shows detailed descriptions of experimental set-up and procedures used in the laboratory tests. This chapter also enlists mathematical equations used to analyze the experimental data.

Chapter 4 covers the results obtained from the flow experiments in horizontal pipe under various conditions such as two different pipe materials (stainless steel and nylon), three surfactant formulations (Cedepal FA-406, Stepanform-1050, and Aquet-944), and three surfactant concentrations (0.1, 0.5, and 5 wt%). A visual analysis of the flow experiments is performed with an aim to characterize foam flow, which agrees with two-flow-regime concept. Results are followed by discussions, and their implications on foam underbalanced drilling and foam fracturing.

Chapter 5 provides the results obtained from the flow experiments at five different flow directions: horizontal (i.e., inclination angle = 0°), 45° upward, 90° upward, 45° downward, and 90° downward for a nylon pipe using 0.5 wt % concentration of Cedepal FA-406 surfactant. A visual analysis of the flow experiments is provided to show the effect of inclination on foam rheology in pipes.
Chapter 6 presents further discussions on the two-flow-regime concept. This includes a comparison of this study with foam models and data in the literature, a comparison with flow regime maps from existing multiphase flow studies, implications in foam drilling hydraulics, and a statistical analysis of the pressure data.

Chapter 7 presents the conclusions drawn on the basis of experimental results followed by recommendations for future studies.

In addition, Appendix A through D provide detailed pressure data collected during this study to support results and discussion in Chapter 4 and 5.
CHAPTER 2

LITERATURE REVIEW

This chapter briefly describes the fundamental concepts associated with foams, foam rheology in pipes, and foam field applications. It also reviews existing foam modeling efforts in the literature, followed by the studies pertinent to foam flow in inclined pipes.

2.1 Foams in General

Foams have been popular in many of daily household activities and industrial applications for many decades. The presence of foams is desirable in some applications such as cutting and proppant transport, liquid unloading, and fire fighting, while the formation of foams is undesirable in other applications such as gas-liquid separation, waste-water treatment, and waste-water flow management in sewage pipes (Kraynik, 1988; Schramm and Wasimuth, 1994; Valko and Economides, 1997; Békkour et al., 1998; Rouyer et al., 2005; Yang et al., 2007; Ruzicka et al., 2009; Kremleva et al., 2010; Duan et al., 2010).

It is the complex structure of foams that makes foam flow interesting and challenging. Although foam is a mixture of gas and liquid, it exhibits metastability with a finite shear modulus just like the way typically observed in solids. The versatility of foams comes from its solid-like structure with compressible gas, low fluid density with high viscosity, and resistance to external disturbance with yield stress (Clark and Blackman, 1948; Prud’homme, 1981; Princen, 1983; Yoshimura et al., 1987; Gardiner et al., 1998; Kam et al., 2002; Kam and Rossen, 2002). Foams in dynamic motion during shear flow in pipes and annuli add another complexity to the properties of bulk foams in a static condition (Hirasaki and Lawson, 1985; Weaire et al., 2003; Langevin et al., 2004).
The use of foams can also be easily spotted in numerous parts of the petroleum industry. When properly managed and designed, foam treatments can take great advantage of its high solids-carrying capacity, minimum filtration, and circulation losses. Many of these features are strongly desired in drilling and fracturing operations in the petroleum industry, by transporting rock cuttings and proppants effectively and minimizing the formation damage with a reduced amount of aqueous phase (Schramm, 1994; Bonilla and Shah, 2000; Saintpere et al., 2003; Affonso et al., 2004; Capo et al., 2006). Previous foam studies show that it may require a tremendous amount of efforts to achieve and maintain the desired foam properties, and furthermore the results at certain test conditions may not be easily translated into different conditions when it comes to up-scaling and down-scaling issues.

Although it is somewhat different from bulk foam flow in pipes or annuli by its nature, foam has also been popular in reservoir or subsurface applications, not only in small-scale near-wellbore production enhancement but also in large-scale mobility control and sweep-efficiency improvement (Patton et al., 1983; Kovscek et al., 1995; Rossen et al., 1999; Lakatos et al., 2003; Li et al., 2008; Kam, 2008).

2.2 Foam Flow in Pipes and Annuli

Foam flow in pipes and annuli has been extensively investigated in many decades as shown by some early studies of Sibree (1934), Grove (1951), and Mitchell (1969) which focused on foam rheology as a function of injection foam quality (or, the ratio of gas injection velocity to total injection velocity). A comprehensive summary is also available as shown in Okpobiri and Ikoku (1986), Heller and Kuntamukkula (1987), and Despande and Barigou (2000).
Bulk-foam rheology in pipes is shown to be very complicated and strongly influenced by numerous parameters including temperature, pressure, foam quality (i.e., gas fraction), foam texture (or bubble size), fluid-wall interactions, external liquid-phase properties, and type and concentration of the surfactants (Bonilla et al., 2000; Guzman et al., 2005). Other additives such as guars, polymers, and gels are often formulated together to endow foams with better stability and higher viscosity (Reidenbach et al., 1986; Harris and Heath, 1996; Sani and Shah, 2001; Khade and Shah, 2004; Hutchins and Miller, 2005).

As observed by Patton et al. (1983), it is typical that foam viscosity can be of several orders of magnitude greater than the viscosity of external liquid phase. Efforts have been made to model the rheological properties of foams for decades, mostly using different types of fluid models. Many of those studies show that foam viscosity decreases with increasing shear rate, which is the conventional behavior of Ostwald-de Waele pseudo-plastic fluid (Raza and Marsden, 1967; David and Marsden, 1969; Sanghani and Ikoku, 1983). This allows foam rheology to be modeled by a two-parameter equation, well known as the power-law model. Other studies such as Mitchell (1969), Blauer et al. (1974), and Calvert and Nezhati (1986) report a noticeable magnitude of yield stress and describe foam rheology using a yield stress and a plastic viscosity, so-called the Bingham-plastic model. Putting these two models together, it is possible to come up with a general three-parameter model, known as the Hershel-Bulkley model, as Saintpere et al. (1999) suggested from their foam study for underbalanced drilling.

No matter which foam models are used, it is certain that foam viscosity is strongly affected by foam quality and texture. Previous experiments with increasing foam quality at a fixed total injection velocity show that there is a threshold value of foam quality ($f_g$), $f_{gth}$ as shown in Fig. 2.1, which can distinguish different types of foam flow characteristics (David and
Marsden, 1969; Blauer et al., 1974; Harris and Heath 1996; Briceno and Joseph, 2003): (1) for \( f_g < f_{gth} \), apparent foam viscosity (\( \mu_{app} \)) does not change significantly but increases with foam quality (\( f_g \)) gradually and (2) for \( f_{gth} < f_g \), the viscosity increases dramatically with foam quality due to bubble-to-bubble interactions.

![Figure 2.1: A schematic showing changes in apparent foam viscosity (\( \mu_{app} \)) as a function of foam quality at fixed total injection velocity.](image)

Although the rheology of foams is affected by the presence of other chemical agents such as polymers and gels, it still seems to follow this basic trend reasonably well (Harris and Heath, 1996; Bonilla and Shah, 2000). The rheology of bulk foam can be even more complicated because (i) foam mixture is not typically moving at the same velocity with the liquid accumulated at the bottom or at the wall of the flow conduit and (ii) the bubbles within the foam mixture may not be necessarily moving together as a single homogeneous phase. These additional complexities are reported by Briceno and Joseph (2003) and Peysson and Herzhaf (2008) using the concept of the lubrication effect and the drainage effect.
Lubrication effect represents the effect of wall boundary condition and the flow mechanism of foams in the presence of wall-slip. The thin layer does not slip but provides lubrication to the flow by wetting the wall by the liquid. It has been considered as fluidity component for the description of foams (Princen, 1983). In the presence of thin liquid layer, foams can be transported entirely as a plug flow, as reported by Beyer et al. (1972), Kraynik (1988), and Thondavadi and Lemlich (1985).

The phenomenon of self-lubrication was explored by Briceno and Joseph (2003) for foam flow in pipe. They observed that self-lubricating foam moves as a rigid body, and the lubricated layer is formed by breaking and healing the foam at the wall. The main principle behind the self-lubrication is that it is easier to break the foam, rather than deform it, which leads to liquid accumulation locally and hence lubrication. This phenomenon has been incorporated into foam flow applications in underbalanced drilling, as shown by Peysson and Herzhaft (2008) for pressure drop estimation.

Foams with a high liquid fraction face liquid drainage, as the spherical bubbles with thick liquid films are subjected to drainage due to gravity. Weisman and Calvert (1967) mentioned that liquid drainage proceeds at considerably faster rates in flowing foam compared to stagnant foam. The drainage rate is shown to depend on the physical properties of foaming solutions, especially viscosity and surface tension. As a result of liquid drainage, liquid films become thicker at the bottom of the foams compared to the top. Drainage helps place the larger bubbles at the top and smaller at the bottom, forming quality gradient across foams vertically. A micro-scale analysis of the drainage effect has been explored by Nguyen (2001), Koehler et al. (2004), Neethling (2006), and Stevenson et al. (2007).
2.3 Effect of Inclination on Bulk Foam Rheology

The direction of foam flow is an important parameter because a well trajectory often consists of vertical, inclined, and horizontal segments (e.g. directional and horizontal drilling), the flow of interest can be either upward or downward (e.g. downward foam flow into the drilling pipe followed by upward foam flow along the annulus), and the efficiency of solid transport is inclination-dependent (e.g. cutting transport in horizontal/inclined wells and upward movement of foamed cement slurry). As pointed out by Despande and Barigou (2000), most foam flow studies are based on certain inclination angle to meet the specific goals of field applications.

An example of such studies is given by Capo et al. (2006) which specifically examined the effect of inclination angle on the efficiency of cutting transport, by carrying out the experiments in a range of solid concentrations. They carried out experiments on a 90 ft. long flow loop with an 8-inch inner-diameter transparent casing and a 4.4-inch outer-diameter drill pipe. Their study showed that the cutting transport efficiency at 45° inclination was better than those at 55° and 65° inclination for 70% foam quality, and lower foam quality (70%) performed better than higher foam quality (80%).

Martins et al. (2001) experimentally examined the performance of foams in hole cleaning within horizontal (0°) and inclined (45° and 75°) well geometries. The hole cleaning performance was poor in the inclined wells (45° and 75°) as compared to the horizontal well. The results at 45° were very similar to 75° inclination though. The results showed that an increase in total rate as well as a reduction in gas fraction (or foam quality) generally resulted in improved hole-cleaning performance, and this effect was more pronounced when the inclination angle was 0° (or horizontal). They also proposed a model to predict hole cleaning while under-balanced or near-
balanced drilling conditions in horizontal wells as a function of foam quality and mixture Reynolds number.

Osunde and Kuru (2006) investigated the mechanisms of cutting transport during drilling processes in inclined wells by performing 1D numerical modeling and transient simulation studies. Their model was constructed based on the assumption that foam behaved as a power-law fluid. The model could predict the optimum foam flow rate (i.e. liquid and gas rates) which maximized the cutting transport efficiency at a given inclination angle. Their model was validated by using data from Capo et al. (2006) with an error range from 4.65 % to 21.65 %.

The study of Guo et al. (2003) provides initial efforts to calculate bottomhole pressure when drilling with foam in a deviated hole using analytical models. Their model was similar to the model of Okpobiri and Ikoku (1986), but neglected solid friction factor of cuttings, which resulted in lower bottomhole pressure prediction. This model accounted for the frictional and hydrostatic pressure components in vertical and inclined wellbores, and was validated using bottomhole data from two wells drilled with stable foams in Parana basin, Brazil, where 12-1/4” hole section was drilled with nitrogen foam for the depth from 152 to 1300 meter.

A study by Saintpere et al. (2003) evaluated the hole cleaning capability of foams in terms of the dimensionless parameter such as Herschel-Bulkley number ($H_b$, the ratio of yield stress to viscous stress), specific volume expansion ratio ($\epsilon_s$, the ratio of foam volume to the specific volume of the base fluid) and shear thinning index (n) at different inclination angles (0-90°). The results showed that $H_b$ and $\epsilon_s$ had a strong correlation with hole cleaning efficiency.

The study of Chen et al. (2009) with polymer-thickened foams examined the effect of inclination on foam properties such as foam quality, density, and velocity, showing the profiles of pressure, foam quality, velocity and density at different inclination angles. The addition of
polymers increased the viscosity and density of foams, and caused a change in pressure profile and foam quality. The change in foam quality due to the compression of gas phase ranged from 77% to 67% for the vertical well, from 84% to 75% for the directional well (45° inclination angle), and from 86% to 77% for the horizontal well. They noticed that the foam properties in vertical wells changed more dramatically than inclined and horizontal wells.

Even though these experimental studies show results at different flow directions, there is a lack of experimental study showing how foam rheology changes as a function of inclination angle by keeping other test conditions identical.
CHAPTER 3

METHODS AND MATERIALS

This chapter describes the materials and equipment used for foam flow experiments. The experimental procedure is also outlined followed by data analysis.

3.1 Experimental Set-up and Materials

For experiments in horizontal direction (Chapter 4), an apparatus to inject nitrogen gas and surfactant solutions into a pipe was set up as schematically shown in Fig. 3.1. The surfactant solution with a pre-specified surfactant concentration stored in a beaker was pumped into the pipe by using Optos 3HM pump (Eldex, CA) which had the flow rate range of 0.04-80 cm³/min (or, 6.66 x 10⁻⁹ - 1.33 x 10⁻⁶ m³/s). A high-pressure (2500 psi) nitrogen gas cylinder supplied the gas phase, which was regulated by a 5850E Brooks mass flow controller (Brooks Instruments, PA). Pre-determined gas and liquid surfactant flow rates were then applied and maintained until the flow was believed to reach a steady state. A visual cell was placed upstream of the pipe so that one could examine the mixture of gas and liquid before entering the pipe. A filter with 50- or 90-µm opening size was installed upstream of the visual cell in order to artificially create fine-textured foams for testing purpose if needed, but the filter was bypassed in all experiments reported here.

Two different pipe materials were used in the experiments: one with stainless steel and the other with nylon. The stainless steel pipe was 11.94 ft (or, 3.63 m) in length and 0.36/0.5 inch (or 0.0091/0.012 m) in inner/outer diameters, and the nylon pipe was 12.58 ft (or, 3.83 m) in length and 0.38/0.5 inch (or 0.0096/0.012 m) in inner/outer diameter.
The nylon pipe was transparent so that one could see through the pipe to investigate flow patterns and bubble size distribution. Eight Omega pressure transducers (Omegadyne Inc., OH) were installed to measure the sectional pressure drops along the pipe. These pressure transducers, named port A through port H, were roughly equally spaced - about 20.47 inches (or, 0.51 m) and 21 inches (or, 0.53 m) apart from each other for stainless steel and nylon pipes, respectively - with the first one installed right after the inlet of the pipe, the last one installed right before the end of the pipe, and six others installed in between. The measured pressure data from the transducers were transmitted to the data gathering system on a real-time basis. The fluids were collected and disposed at the outlet of the pipe. For the experiments with a nylon pipe, the flow was photographed and videotaped near the outlet. The tubing upstream of the pipe was constituted with 1/8 and 1/4 inch inner and outer diameters respectively.

Figure 3.1: Experimental set-up for foam flow in horizontal pipe.
Three different surfactants were used in the flow experiments - Cedepal FA-406 (Stepan, IL), Stepanform-1050 (Stepan, IL), and Aquet-944 (Baker Petrolite, TX). They were anionic surfactants typically used in drilling and fracturing applications in the petroleum industry.

For experiments in different flow directions (Chapter 5), a new set-up was built-up to accommodate various inclination angles and flow directions as shown by the actual photograph in Fig. 3.2. The pipe made of Nylon 6 (McMaster-Carr, GA) was installed on a wooden arm which could be adjusted to any inclination angles (i.e., from 0° to 90°, with the flow either upward or downward) with the help of a magnetic compass angle finder attached at the center of the arm. Other devices and specifications (i.e. pump, pressure transducers, gas flow meter and data acquisition system) were same as those in horizontal pipe experiments. Movies were taken at the section between pressure transducers C and D. Cedepal FA-406 at the concentration of 0.5 wt.%, typically applied in the field, was selected for the inclined pipe experiments. Five inclination angles were selected: upward (45° and 90°), downward (45° and 90°), and horizontal directions.

3.2 Procedure

The flow experiments were carried out by following the steps described below once the inclination is decided:

1) Prepare a surfactant solution of desired formulation, concentration, and quantity. The concentration of surfactant solution in this study is expressed in percent of total weight (wt %).

2) Inject the surfactant solution first at a pre-specified value until the solution is produced at the outlet.
Figure 3.2: Laboratory set-up for flow experiments in different inclination angles.

3) Inject nitrogen gas at a pre-specified value using a gas mass flow controller.

4) Make sure from the visual cell upstream that the mixture of gas and surfactant solutions flows into the pipe together.

5) Activate the data acquisition system (this step can be placed before step 2), and continue to inject gas and surfactant solutions at pre-specified values until the pressure response reaches a steady state. For the range of injection velocities applied in this study, a steady state can be commonly achieved within several to ten minutes.

Most of the experiments in this study were carried out at one fixed value of liquid velocity, either monotonically increasing or decreasing gas velocity step by step. The nominal liquid velocities were 0.017, 0.033, 0.050, and 0.067 ft/s (i.e., 20, 40, 60, 80 cm³/min, or 3.3x10⁻
7, 6.66x10^{-7}, 1x10^{-6}, 1.33x10^{-6} m^3/s, respectively) with gas velocity ranging from 0.082 to 3.590 ft/s (i.e., 100 to 5,000 cm^3/min, or 1.66x10^{-6} to 8.33x10^{-5} m^3/s at standard conditions) for 0.36-inch inner diameter stainless-steel pipes.

For the nylon pipe, inner diameter (d) was 0.38 inches (or, the cross-sectional area (A) of 0.113 inch^2), the nominal liquid velocities tested (u_w) were 0.014, 0.029, 0.044, and 0.059 ft/s (or, 3.33x10^{-7}, 6.66x10^{-7}, 10x10^{-7}, and 1.33x10^{-6} m^3/s) corresponding to the liquid rates (Q_w) of 20, 40, 60, and 80 cm^3/min respectively, and the nominal gas velocities tested (u_g) were from 0.149 to 3.73 ft/s (or 0.0455 to 1.139 m/s) at the standard condition corresponding to the gas rates (Q_g) 200 to 5,000 cm^3/min (or 3.33x10^{-6} to 8.33x10^{-5} m^3/s).

3.3 Data Analysis

The pressure data obtained from the experiments on a real-time basis can be time-averaged when the steady-state condition is reached. These pressure values are used to determine the sectional pressure drops, which then can be translated into the apparent foam viscosities (\( \mu_{app} \)). The contour plots can be constructed based on either the pressure drop or the apparent viscosity.

For foam flow with gas and surfactant solutions injected together, the total flow rate (Q_t) is simply the addition of gas flow rate (Q_g) and liquid flow rate (Q_w), i.e.,

\[
Q_t = Q_w + Q_g
\]  (3-1)

which is essentially the same as the following equation using the superficial velocities:

\[
u_t = u_w + u_g
\]  (3-2)
where \( u_t, u_w \) and \( u_g \) are the total, liquid, and gas superficial velocities. Note that the superficial velocity of phase \( j \) (\( u_j \)) is defined as the flowrate of the phase (\( Q_j \)) divided by the cross-sectional area (\( A \)) of the pipe, i.e., \( u_j = Q_j / A \), where \( A = \pi d^2 / 4 \), with \( d \) being the inner diameter.

The shear stress at the wall, if the flow conduit is cylindrical, can be expressed by

\[
\tau_w = 3 \left( \frac{d \Delta p}{L} \right) , \hspace{1cm} (3-3)
\]

where \( \tau_w \) is the wall shear stress [lbf/ft²], \( \Delta p \) is the pressure drop [psi], and \( d \) and \( L \) are the diameter in [inch.] and length of the corresponding pipe segment in [ft].

The shear rate for the flow in pipe is given by

\[
\gamma_w = 39.216 \left( \frac{Q_t}{d^2} \right) , \hspace{1cm} (3-4)
\]

where, \( \gamma_w \) is the wall shear rate [sec⁻¹], \( Q_t \) is the total flow rate [gal/min], and \( d \) is the pipe inner diameter [in].

The apparent foam viscosity is then calculated as follows:

\[
\mu_{app} = 47880 \left( \frac{\tau_w}{\gamma_w} \right) , \hspace{1cm} (3-5)
\]

where \( \mu_{app} \) is the apparent foam viscosity [cp], \( \tau_w \) is the shear stress [lbf/ft²], and \( \gamma_w \) is the wall shear rate [sec⁻¹].
CHAPTER 4

RESULTS AND DISCUSSIONS: FOAM FLOW IN HORIZONTAL PIPE

Before starting major flow experiments in horizontal direction, a few laboratory tests were carried out to understand the properties of surfactant solutions used in this study. The summary is shown in Table 4.1. Interfacial tension was measured by pendant drop method (Adamson, 1976) which analyzed the shape of liquid droplets. Example measurements at 0.1 and 0.5 wt% surfactant concentrations for different surfactant formulations are shown in Fig. 4.1 and Fig. 4.2 respectively.

Table 4.2 shows the list of 9 different series of experiments conducted in horizontal pipe (Base Case and Cases 1 through 8) which are described more in detail in the following sections. In addition, the characteristics of three different surfactants are compared in Table 4.3 based on the information provided in the material safety data sheet (MSDS) delivered from the manufacturers.

Table 4.1 Density and Surface Tension of Surfactant Samples

<table>
<thead>
<tr>
<th>Surfactant</th>
<th>Surfactant conc. wt.%</th>
<th>Density, g/cm³</th>
<th>Surface Tension, dyne/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cedepal FA-406</td>
<td>0.1</td>
<td>0.9963</td>
<td>59.73</td>
</tr>
<tr>
<td>Cedepal FA-406</td>
<td>0.5</td>
<td>0.9979</td>
<td>40.36</td>
</tr>
<tr>
<td>Cedepal FA-406</td>
<td>5</td>
<td>1.004</td>
<td>37.91</td>
</tr>
<tr>
<td>Stepanform-1050</td>
<td>0.1</td>
<td>0.9977</td>
<td>36.40</td>
</tr>
<tr>
<td>Stepanform-1050</td>
<td>0.5</td>
<td>0.9981</td>
<td>37.42</td>
</tr>
<tr>
<td>Aquet-944</td>
<td>0.1</td>
<td>0.9979</td>
<td>35.19</td>
</tr>
<tr>
<td>Aquet-944</td>
<td>0.5</td>
<td>0.9979</td>
<td>35.45</td>
</tr>
<tr>
<td>Aquet-944</td>
<td>5</td>
<td>0.999</td>
<td>34.60</td>
</tr>
</tbody>
</table>
Figure 4.1: Shape of the droplet for the surface tension measurement using pendent drop method (Surfactant concentration 0.1 weight % for a) Cedepal FA-406, b) Stepanform-1050, and c) Aquet-944)

Figure 4.2: Shape of the droplet for the surface tension measurement using pendent drop method (Surfactant concentration 0.5 weight % for a) Cedepal FA-406, b) Stepanform-1050, and c) Aquet-944)

<table>
<thead>
<tr>
<th>Cases</th>
<th>Pipe size and Material</th>
<th>Surfactant Type and Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>OD 0.5” Stainless Steel</td>
<td>Cedepal FA-406, 0.5 wt%</td>
</tr>
<tr>
<td>1</td>
<td>OD 0.5” Stainless Steel</td>
<td>Cedepal FA-406, 0.1 wt%</td>
</tr>
<tr>
<td>2</td>
<td>OD 0.5” Stainless Steel</td>
<td>Cedepal FA-406, 5.0 wt%</td>
</tr>
<tr>
<td>3</td>
<td>OD 0.5” Stainless Steel</td>
<td>Stepanform-1050, 0.5 wt%</td>
</tr>
<tr>
<td>4</td>
<td>OD 0.5” Stainless Steel</td>
<td>Stepanform-1050, 0.1 wt%</td>
</tr>
<tr>
<td>5</td>
<td>OD 0.5” Nylon 6 Transparent</td>
<td>Cedepal FA-406, 0.5 wt%</td>
</tr>
<tr>
<td>6</td>
<td>OD 0.5” Nylon 6 Transparent</td>
<td>Aquet-944, 5 wt%</td>
</tr>
<tr>
<td>7</td>
<td>OD 0.5” Nylon 6 Transparent</td>
<td>Aquet-944, 0.5 wt%</td>
</tr>
<tr>
<td>8</td>
<td>OD 0.5” Nylon 6 Transparent</td>
<td>Aquet-944, 0.1 wt%</td>
</tr>
</tbody>
</table>
Table 4.3 Comparison of Surfactant Characteristics

<table>
<thead>
<tr>
<th>Properties</th>
<th>Cedepal FA-406</th>
<th>Stepanform-1050</th>
<th>Aquet-944</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Anionic</td>
<td>Anionic</td>
<td>Anionic</td>
</tr>
<tr>
<td>Chemical Class</td>
<td>Ammonium Alcohol Ether Sulfate 57-60%; Ethanol 13-16%</td>
<td>Isopropanol 2-5%; Anionic Blend 50-60%; (Confidential) Water 37-40%; Formaldehyde &lt;400ppm</td>
<td>Isopropanol 10-30%</td>
</tr>
<tr>
<td>pH</td>
<td>7-7.5</td>
<td>6.5-7.5</td>
<td>6-9.5</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1.03 g/ml @25°C</td>
<td>1.0817 g/ml @25°C</td>
<td>1.031 g/ml @16°C</td>
</tr>
<tr>
<td>Viscosity</td>
<td>20 cp @25°C</td>
<td>100-200 cps @25°C</td>
<td>176-194 @16°C</td>
</tr>
<tr>
<td>Solubility (Water)</td>
<td>Soluble</td>
<td>Soluble</td>
<td>Soluble</td>
</tr>
</tbody>
</table>

4.1 Experiments in Stainless-Steel Pipes (0.36/0.5 inch ID/OD): Base Case and Cases 1 - 4

4.1.1 Base Case

Base-Case experiments are conducted by using Stepan FA-406 surfactant at 0.5 wt% concentration. As shown in Fig. 4.3, the pressure response is collected by changing superficial gas velocity \( (u_g) \) step by step in all pressure ports from A through H at fixed superficial liquid velocities \( (u_w) \). Figs 4.3(a), 4.3(b), 4.3(c), and 4.3(d) show the results at four superficial liquid velocities such as 0.017 ft/s \( (0.0051 \text{ m/s}) \), 0.033 ft/s \( (0.010 \text{ m/s}) \), 0.050 ft/s \( (0.015 \text{ m/s}) \), and 0.067 ft/s \( (0.020 \text{ m/s}) \), corresponding to liquid flowrates of 20, 40, 60, and 80 cm\(^3\)/min (or 3.3x10\(^{-7}\), 6.66x10\(^{-7}\), 10x10\(^{-7}\), and 1.33x10\(^{-6}\) m\(^3\)/s, equivalently). For example, when the liquid velocity \( (u_w) \) is at 0.017 ft/s \( (or, Q_w=20 \text{ cm}^3/\text{min}) \) in Fig. 4.3(a), the experiment starts with gas
velocity \( (u_g) \) of 0.083 ft/s (or, \( Q_g=100 \) cc/min) which essentially increases to 3.312 ft/s (or, \( Q_g=4000 \) cc/min) step by step, and then reduced back down to 0.083 ft/s (or, \( Q_g=100 \) cc/min) again. The steady-state pressure value increases dramatically until it reaches a maximum at the gas velocity of 1.243 ft/s (or, \( Q_g=1500 \) cc/min), followed by a rapid reduction at higher gas velocity (or higher foam quality). The entire plot with two pressure humps seems symmetric and mirror-imaged, meaning that there is no hysteresis involved in this process. It should be mentioned that the pressure response at higher foam quality is relatively unstable and oscillating, and the pressure response at lower foam quality is relatively stable. This feature is explained more in visualization experiments later.

Figure 4.3 (a): Pressure response of Base Case (0.5 wt% FA-406, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 20 cm³/min.
Figure 4.3 (b): Pressure response of Base Case (0.5 wt% FA-406, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 40 cm$^3$/min.

Figure 4.3 (c): Pressure response of Base Case (0.5 wt% FA-406, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 60 cm$^3$/min.
Figure 4.3 (d): Pressure response of Base Case (0.5 wt% FA-406, 0.36/0.5”ID/OD stainless-steel pipe) at fixed liquid injection rate of 80 cm³/min.

Fig. 4.4 shows the same experimental data as in Fig. 4.3(b), now plotted for pressure as a function of distance from the inlet by using the pressure data measured at 8 different pressure ports (i.e., port A through H). Because of the symmetric response in Fig. 4.3, only the response for the increasing gas velocity (i.e., the first half of Fig. 4.3(b)) is presented. Note that the pressure response which monotonically increases with gas velocity up to \( u_g =1.243 \text{ ft/s} \) (or, \( Q_g=3000 \text{ cc/min} \)) is shown in Fig. 4.4(a), while the pressure response which monotonically decreases with gas velocity for \( u_g \) greater than 1.243 ft/s (or, \( Q_g=3000 \text{ cc/min} \)) is shown in Fig. 4.4(b). It should be pointed out that the pressure measurement at port C somewhat deviates from the trend. It is because of malfunctioning of the pressure transducer which was re-calibrated and corrected in the following experiments.
The pressure data provided in Figs. 4.3 and 4.4 can be used to obtain the sectional pressure drops exerted by foams and be translated into the apparent foam viscosities. The pressure values measured at the first and last pressure ports (i.e., port A and port H) are not taken into consideration in this analysis due to possible inlet and outlet effects. As a result, the pressure drop between port B and port G (\(\Delta P_{BG}\)) is used in the flow analysis. (Note that the notation \(\Delta P_{ij}\) represents the pressure difference between pressure port i and j, therefore, \(\Delta P_{BG} = P_B - P_G\).) After looking into the pressure data, it is believed that \(\Delta P_{BG}\) truly represents the pressure response of the entire system, because the injected foam adjusts its texture quite rapidly to reach the steady-state texture, and the same texture and flow patterns are typically maintained within the length scale of the pipes in this study, as observed in the pressure measurements and visual images.

Figure 4.4(a): Base Case pressure response as a function of distance (0.5 wt\% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at \(u_w = 0.033\) ft/s (or \(Q_w = 40\) cm\(^3\)/s).

<table>
<thead>
<tr>
<th>Qg, [SCCM]</th>
<th>Pressure, [psi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>25.00</td>
</tr>
<tr>
<td>1000</td>
<td>20.00</td>
</tr>
<tr>
<td>1500</td>
<td>15.00</td>
</tr>
<tr>
<td>2000</td>
<td>10.00</td>
</tr>
<tr>
<td>2500</td>
<td>5.00</td>
</tr>
<tr>
<td>3000</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Distance, [ft]
Fig. 4.5(a) summarizes the values of $\Delta P_{BG}$ in Figs. 4.3(a) through 4.3(d) in a wide range of gas and liquid velocities, as a function of “adjusted” superficial gas velocity, that is, the superficial gas velocity ($u_g$) adjusted at the average pressure within the pipe (i.e., $(P_B + P_G)/2$). At each given liquid velocity, there is a pair of $\Delta P_{BG}$ values reported - one outbound (i.e., increasing gas velocity) symbolized by filled marks and the other inbound (i.e., decreasing gas velocity) symbolized by open marks. The same $\Delta P_{BG}$ plot is constructed as a function of foam quality in Fig. 4.5(b). Figs. 4.5(a) and 4.5(b) show that (1) there is a threshold value of gas velocity ($u_g$) or foam quality ($f_g$) below which the pressure drop ($\Delta P_{BG}$) monotonically increases with increasing $u_g$ or $f_g$. 

Figure 4.4(b): Base Case pressure response as a function of distance (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at $u_w = 0.033$ ft/s (or $Q_w = 40$ cm$^3$/s).
Figure 4.5(a): Base Case pressure response as a function of gas velocity at four different liquid velocities (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe)

Figure 4.5(b): Base Case pressure response as a function of foam quality at four different liquid velocities (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe)
Figure 4.6(a): Base Case shear stress as a function of shear rate at four different liquid velocities (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe)

Figure 4.6(b): Base Case foam viscosity as a function of foam quality and shear rate at four different liquid velocities (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe)
ug or fg, and above which the pressure drop (ΔPBG) monotonically decreases with increasing ug or fg, and (2) the magnitude of pressure drop (ΔPBG) increases as total velocity (ut) increases at the same foam quality. It is of paramount importance in many applications to estimate or predict the value of f_g*, which is, fg at which the peak in pressure drop (ΔPBG) takes place. Note that the results in Fig. 4.5(b) show the value of f_g* decreases with increasing liquid velocity, which is further discussed with pressure contours in later sections.

The pressure data in Figs. 4.5(a) and 4.5(b) can be converted into apparent foam viscosity, shear stress, and shear rate by using Eqs. (3-3), (3-4), and (3-5) as shown in Fig. 4.6. Fig. 4.6(a) with the shear stress (τ_w) as a function of the wall shear rate (γ_w), and Fig. 4.6(b) with the apparent viscosity (µ_app) as a function of the wall shear rate (γ_w) or foam quality (f_g).

These pressure data and calculated apparent viscosity values can be plotted in a form of contours as shown in Figs. 4.7(a) and 4.7(b), respectively, with liquid velocity on the x axis and gas velocity on the y axis. The boxed numbers in Fig. 4.7(a) are the measured pressure drop in [psi] from ΔPBG over 8.58-ft distance between pressure ports B and G, and the boxed numbers in Fig. 4.7(b) are the corresponding apparent viscosity in [cp]. As demonstrated by Figs. 4.3 through 4.6, f_g* at which the peak in ΔPBG or µ_app occurs splits the entire domain into two pieces so-called high-quality regime and low-quality regime. These contour plots show that (1) in the low-quality regime, ΔPBG and µ_app are relatively independent of liquid velocity but sensitive to gas velocity, exhibiting the contours almost horizontal, and (2) in the high-quality regime, ΔPBG and µ_app decrease with gas velocity at fixed liquid velocity, exhibiting the contours with finite slopes. These two distinct regimes are caused by different foam-flow characteristics and patterns, which are further explained in the later visual experiment section.
Figure 4.7(a): Pressure contours of the Base Case with liquid velocity on x axis and gas velocity on y axis (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state pressure drop in [psi].

Figure 4.7(b): Apparent viscosity contours of Base Case with liquid velocity on x axis and gas velocity on y axis (0.5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state apparent foam viscosity in [cp].
As pointed out in Fig. 4.7(b), $f_g^*$ is not a constant, rather the locus bends concavely as liquid velocity increases.

One may wonder why the response in terms of $\mu_{app}$ somewhat different from that in terms of $\Delta P_{BG}$, by comparing Fig. 4.5(b) and Fig. 4.7(b), or Fig. 4.7(a) and Fig. 4.7(b). It is because of the finite number of the data points obtained from the experiments. The shape of these plots would be identical, if an infinite number of pressure data points were available.

4.1.2 Effect of Surfactant Concentrations (Case 1 and Case 2)

Flow experiments similar to the base case are repeated at two other surfactant concentrations such as 0.1 and 5 wt%, referred to as Case 1 and Case 2 respectively. Other conditions are kept identical to the base case by using 0.5-inch OD stainless steel pipe at the same four liquid velocities ($u_0$) such as 0.017 ft/s (0.0051 m/s), 0.033 ft/s (0.010 m/s), 0.050 ft/s (0.015 m/s), and 0.067 ft/s (0.020 m/s), corresponding to liquid flowrates of 20, 40, 60, and 80 cm$^3$/min (or 3.3x10$^{-7}$, 6.66x10$^{-7}$, 10x10$^{-7}$, 1.33x10$^{-6}$ m$^3$/s, equivalently). The overall pressure responses at different surfactant concentrations are comparable with those in Fig. 4.3 of the base case: The trend shows that, at fixed liquid velocity, the pressure increases monotonically with increasing gas velocity up to $f_g^*$, then decreases monotonically with increasing gas velocity beyond that. Details of these pressure data during the experiments in Case 1 and Case 2 are included in Appendix A.

Figs. 4.8(a) and 4.8(b) show the pressure response and apparent viscosity respectively, when 0.1 wt% FA-406 surfactant solution is applied in Case 1. Note that these figures can be contrasted with Figs. 4.5(b) and 4.6(b) of the base case.
Figure 4.8(a): Pressure response of Case 1 as a function of foam quality at four different liquid velocities (0.1 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe).

Figure 4.8(b): Foam viscosity of Case 1 as a function of foam quality and shear rate at four different liquid velocities (0.1 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe).
Figure 4.9(a): Pressure contours of Case 1 with liquid velocity on x axis and gas velocity on y axis (0.1 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state pressure drop in [psi].

Figure 4.9(b): Apparent viscosity contours of Case 1 with liquid velocity on x axis and gas velocity on y axis (0.1 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state apparent foam viscosity in [cp].
The results show that the peak in pressure drop between ports B and G (ΔP_{BG}) and the peak in resulting apparent viscosity (μ_{app}) take place at lower foam quality. The absolute magnitudes of ΔP_{BG} and μ_{app} are also lower than those of the base case.

When plotted using contours as shown in Figs. 4.9(a) and 4.9(b), it is demonstrated more clearly that the magnitudes of ΔP_{BG} and μ_{app} values are reduced significantly and f'_g values are declined at lower surfactant concentration.

Figs. 4.10(a) and 4.10(b), which can be compared with Figs. 4.8(a) and 4.8(b), show the pressure and apparent viscosity with 5 wt% FA-406 surfactant solution in Case 2. The peaks in ΔP_{BG} and μ_{app} translate towards higher foam quality, and their magnitudes are higher compared with 0.1 or 0.5 wt% FA-406 in Case 1 or the base case. The pressure contours and the apparent-viscosity contours shown in Figs. 4.11(a) and 4.11(b) are also consistent with this observation.

By putting the contours of 0.1, 0.5, and 5 wt% concentrations together, it can be noticed that an increase in surfactant concentration improves foam stability to make the measured pressure drop higher. As a result, the transition from low-quality to high-quality regime (i.e., f'_g) occurs at higher foam quality as surfactant concentration increases. In all three concentrations, the curves connecting f'_g values are concave in the contour plots, meaning that the transition from low-quality to high-quality regime takes place at lower foam quality as liquid velocity increases. It can be generally said that the high-quality regime expands (or the low-quality regime contracts) as foam becomes less stable with lower surfactant concentration.
Figure 4.10(a): Pressure response of Case 2 as a function of foam quality at four different liquid velocities (5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe).

Figure 4.10(b): Apparent viscosity of Case 2 as a function of foam quality and shear rate at four different liquid velocities (5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe).
Figure 4.11(a): Pressure contours of Case 2 with liquid velocity on x axis and gas velocity on y axis (5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state pressure drop in [psi].

Figure 4.11(b): Apparent viscosity contours of Case 2 with liquid velocity on x axis and gas velocity on y axis (5 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state apparent foam viscosity in [cp].
4.1.3 Effect of Surfactant Formulations (Case 3 and Case 4)

The same flow experiments, called Case 3 and Case 4, are carried out by using another anionic surfactant, Stepanform-1050 (Stepan, IL), at two different concentrations of 0.5 and 0.1 wt% respectively. Laboratory foam stability tests show that the stability of Stepanform-1050 is comparable with that of FA-406 at the same surfactant concentrations.

Figs. 4.12(a) and 4.12(b) show the response of pressure and apparent viscosity of Case 3 with 0.5 wt% Stepanform-1050 surfactant solution. Note that these figures can be contrasted with Figs. 4.5(b) and 4.6(b) in which the same concentration of FA-406 is used. Likewise, Figs. 4.13 (a) and 4.13(b) show the results of Case 4 with 0.1 wt% Stepanform-1050 surfactant, which can be contrasted with Figs. 4.8(a) and 4.8(b). As expected from the bulk foam stability tests, the peak values of $\Delta P_{BG}$ and $\mu_{app}$, together with the gas velocity and shear rate at which these peaks take place, are similar.

The pressure and apparent viscosity contours are shown in Figs. 4.14(a) and 4.14(b) for 0.5 wt% (Case 3) and Figs. 4.15(a) and 4.15(b) for 0.1 wt% (Case 4) Stepanform-1050 surfactant solutions. Once again, it is observed that as surfactant concentration decreases, the magnitudes of pressure and apparent viscosity are reduced, and the transition from weak-foam to strong-foam regime takes place at lower foam quality causing the high-quality regime to expand and the low-quality regime to contract.

The effect of surfactant formulation can be observed by comparing Figs. 4.5 (b), 4.12 (a), and 4.20 (a) for FA-406, Stepanform-1050, and Aquet-944 at 0.5 wt %. The pressure response for FA-406 and Stepanform-1050 is similar, while for the pressure response for Aquet-944 is
much smaller due to its poor foamability. Details of these pressure data during experiments in Case 3 and Case 4 are included in Appendix B.

Figure 4.12(a): Pressure response of Case 3 as a function of foam quality at four different liquid velocities (0.5 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe).

Figure 4.12(b): Foam viscosity of Case 3 as a function of foam quality and shear rate at four different liquid velocities (0.5 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe).
Figure 4.13(a): Pressure response of Case 4 as a function of foam quality at four different liquid velocities (0.1 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe).

Figure 4.13(b): Foam viscosity of Case 4 as a function of foam quality and shear rate at four different liquid velocities (0.1 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe).
Figure 4.14(a): Pressure contours of Case 3 with liquid velocity on x axis and gas velocity on y axis (0.5 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state pressure drop in [psi].

Figure 4.14(b): Apparent viscosity contours of Case 3 with liquid velocity on x axis and gas velocity on y axis (0.5 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state apparent foam viscosity in [cp].
Figure 4.15(a): Pressure contours of Case 4 with liquid velocity on x axis and gas velocity on y axis (0.1 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state pressure drop in [psi].

Figure 4.15(b): Apparent viscosity contours of Case 4 with liquid velocity on x axis and gas velocity on y axis (0.1 wt% Stepanform-1050, 0.36/0.5” ID/OD stainless-steel pipe). Values reported represent the steady-state apparent foam viscosity in [cp].
4.2 Experiments in Transparent Nylon Pipes (0.38 inch ID/ 0.5 inch OD): Cases 5 through 8

In order to characterize foam flow in pipe visually, the same experiments were repeated in a see-through transparent pipe made of Nylon 6 (McMaster, GA). Note that the dimension of the nylon pipe is roughly the same as that of the stainless steel pipe. Details of these pressure data during experiments in Case 5-Case 8 are included in Appendix C.

4.2.1 Flow Experiments with FA-406 (Case 5)

Figs. 4.16(a) and 4.16(b) show the response of pressure and apparent viscosity in Case 5 with 0.5 wt% FA-406 in a nylon pipe, which can be contrasted with those in a stainless steel pipe (cf., Figs. 4.5(b) and 4.6(b)). Although the magnitudes of $\Delta P_{BG}$ and $\mu_{app}$ are slightly larger with the nylon pipe, the results in two different types of pipes are comparable. The corresponding contour plots are shown in Figs. 4.17(a) and 4.17(b).

4.2.2 Flow Experiments with Aquet-944 surfactants (Case 6, Case 7, and Case 8)

Another anionic surfactant, Aquet-944 (Baker Petrolite, TX), is tried for flow experiments in the nylon pipe: Figs. 4.18(a), 4.18(b), 4.19(a), and 4.19(b) are the results for 5 wt% in Case 6; Figs. 4.20(a), 4.20(b), 4.21(a), and 4.21(b) are the results for 0.5 wt% in Case 7; and Figs. 4.22(a), 4.22(b), 4.23(a), and 4.23(b) are the results for 0.1 wt% Aquet-944 surfactants.

The effect of surfactant concentration discussed in earlier sections is still applicable: (1) the steady-state pressure drop and apparent viscosity increase with increasing surfactant concentration; and (2) the transition from low-quality regime to high-quality regime takes place at lower foam quality as surfactant concentration decreases, which causes growing high-quality regime (or shrinking low-quality regime, equivalently) with decreasing surfactant concentration.
Figure 4.16(a): Pressure response of Case 5 as a function of foam quality at four different liquid velocities (0.5 wt% FA-406, 0.38/0.5” ID/OD nylon pipe).

Figure 4.16(b): Foam viscosity of Case 5 as a function of foam quality and shear rate at four different liquid velocities (0.5 wt% FA-406, 0.38/0.5” ID/OD nylon pipe).
Figure 4.17(a): Pressure contours of Case 5 with liquid velocity on x axis and gas velocity on y axis (0.5 wt% FA-406, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state pressure drop in [psi].

Figure 4.17(b): Apparent viscosity contours of Case 5 with liquid velocity on x axis and gas velocity on y axis (0.5 wt% FA-406, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state apparent foam viscosity in [cp].

45
Figure 4.18(a): Pressure response of Case 6 as a function of foam quality at four different liquid velocities (5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe).

Figure 4.18(b): Foam viscosity of Case 6 as a function of foam quality and shear rate at four different liquid velocities (5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe).
Figure 4.19(a): Pressure contours of Case 6 with liquid velocity on x axis and gas velocity on y axis (5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state pressure drop in [psi].

Figure 4.19(b): Apparent viscosity contours of Case 6 with liquid velocity on x axis and gas velocity on y axis (5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state apparent foam viscosity in [cp].
Figure 4.20(a): Pressure response of Case 7 as a function of foam quality at four different liquid velocities (0.5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe).

Figure 4.20(b): Foam viscosity of Case 7 as a function of foam quality and shear rate at four different liquid velocities (0.5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe).
Figure 4.21(a): Pressure contours of Case 7 with liquid velocity on x axis and gas velocity on y axis (0.5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state pressure drop in [psi].

Figure 4.21(b): Apparent viscosity contours of Case 7 with liquid velocity on x axis and gas velocity on y axis (0.5 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state apparent foam viscosity in [cp].
Figure 4.22(a): Pressure response of Case 8 as a function of foam quality at four different liquid velocities (0.1 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe).

Figure 4.22(b): Foam viscosity of Case 8 as a function of foam quality and shear rate at four different liquid velocities (0.1 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe).
Figure 4.23(a): Pressure contours of Case 8 with liquid velocity on x axis and gas velocity on y axis (0.1 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state pressure drop in [psi].

Figure 4.23(b): Apparent viscosity contours of Case 8 with liquid velocity on x axis and gas velocity on y axis (0.1 wt% Aquet-944, 0.38/0.5” ID/OD nylon pipe). Values reported represent the steady-state apparent foam viscosity in [cp].
4.3 Visual Observations from Nylon-Pipe Experiments (0.38 inch ID and 0.5 inch OD)

The visual analyses using the transparent nylon pipe are conducted with FA-406 (0.5 wt% as in Case 5) and Aquet-944 (0.5 wt% in Case 7 and 0.1 wt% in Case 8). The flow characteristics such as bubble size and bubble size distribution provide the basis for the characterization of foam flow. The observation through the transparent nylon pipe can be made anywhere from the inlet to the outlet, but the photos and movies are taken at about 1 ft upstream of the outlet where the foam texture is believed to be fully matured and developed.

Fig. 4.24 shows the results with 0.5 wt% FA-406 surfactant in a wide range of gas and liquid velocities (cf. Fig. 4.17). There are a few important characteristics to be noted: (1) the high-quality regime exhibits the pattern of slug flow in which fine-textured foam-slug sections and free-gas (or, very-coarse-foam) sections repeat and alternate each other. This alternating nature of slug flow is reflected by oscillating pressure measurements as shown in earlier figures (cf. Fig. 4.3); (2) the low-quality regime exhibits two different patterns – (i) the flow of homogeneous foams at relatively high \( f_g \) and (ii) a segregated flow in which the liquid phase is accumulated and flows in the lower section of the pipe, and the foam flows in the upper section of the pipe at relatively low \( f_g \). Gas bubbles and liquid migrate roughly at the same velocity forming a plug flow in the former, while bubbles and liquids are segregated with the upper foam layer traveling slower than the lower liquid layer in the latter. In both cases, the pressure response was relatively stable without showing the oscillations in pressure; and (3) the \( f_g^* \) values that split the two flow regimes roughly correspond to the transition between the plug flow in the low-quality regime and the slug flow in the high-quality regime. This explains why the maximum pressure drop or the maximum apparent viscosity occurs near \( f_g^* \).
Figure 4.24: Results from Case 5 visualization analysis near the outlet (i.e., about 1 ft upstream from the outlet) for 0.5 wt% FA-406 surfactant in a wide range of gas and liquid velocities.

In order to better understand the behavior of slug flow in the high-quality regime, further experiments are performed with injection conditions within the high-quality regime only. Figs. 4.25(a) and 4.25(b) show the analysis in terms of the sizes of free-gas section and foam-slug section, respectively. Again, note that the term “free gas” in the high-quality regime represents a state in which no bubbles, or very coarse-textured foams, are present. Fig. 4.25(a) shows that (1) an increase in liquid velocity at the same gas velocity causes the size of free-gas section to decrease, and (2) an increase in gas velocity at the same liquid velocity causes the size of free-gas section to increase. This implies that any change in injection conditions which leads to drier
foams (or, higher foam quality) stretches the size of free-gas section. Similarly, Fig. 4.25(b) shows that (1) an increase in liquid velocity at the same gas velocity causes the size of foam-slug section to increase, and (2) an increase in gas velocity at the same liquid velocity causes the size of foam-slug section to decrease. This implies that any change in injection conditions which leads to drier foams (or, higher foam quality) reduces the size of foam-slug section. It can be inferred that at extremely dry flow conditions, the foam-slug section ultimately disappears leaving only free gas flow, which is consistent with mist flow that other experimental studies observed (Martins et al., 2001).

Figure 4.25(a): Effect of gas and liquid injection velocities on the size of free gas in the high-quality regime.
Figure 4.25(b): Effect of gas and liquid injection velocities on the size of foam slugs in the high-quality regime.

Figs. 4.26 and 4.27 show the results of visualization experiments with Aquet-944 at 0.5 and 0.1 wt% concentrations (Case 7 and Case 8), respectively. The overall responses are similar to those observed in Fig. 4.24 with 0.5 wt% FA-406. The lower surfactant concentration in Fig. 4.27 leads to wider high-quality regime and coarser foam texture compared with the higher surfactant concentration in Fig. 4.26, as expected.
Figure 4.26: Results from Case 7 visualization analysis near the outlet (i.e., about 1 ft upstream from the outlet) for 0.5 wt% Aquet-944 surfactant in a wide range of gas and liquid velocities. The overall response is similar to Fig. 4.24 with 0.5 wt% FA-406.

Figure 4.27: Results from Case 8 visualization analysis near the outlet (i.e., about 1 ft upstream from the outlet) for 0.1 wt% Aquet-944 surfactant in a wide range of gas and liquid velocities.
The results of visual experiments in Figs.4.24 through 4.27 can be summarized as shown by the schematic figure in Fig. 4.28. Two regimes are separated by the trace of $f_g^*$ above which free gas and foam slugs alternate each other, and below which homogeneous foams flow by forming either plug flow or segregated flow. The low-quality regime can be roughly subdivided into four sections depending on total injection velocity and foam quality: (1) relatively high total velocity and high foam quality (the region denoted by “(A)” ) in which the mixture forms plug flow of fine-textured foams; (2) relatively high total velocity and low foam quality (the region denoted by “(B)” ) in which the mixture forms segregated flow of fine-textured foams and underlying liquid; (3) relatively low total velocity and high foam quality (the region denoted by “(C)” ) in which the mixture forms plug flow of foams but with less finer texture than foams in region (A); and (4) relatively low total velocity and low foam quality (the region denoted by “(D)” ) in which the mixture forms segregated flow again, the foams in the upper layer with less finer texture than foams in region (B).

The distinction between the two regions of high total velocity ((A) and (B)) and low total velocity ((C) and (D)) can be described by the change in bubble size as a function of injection velocity. At fixed foam quality, there is a threshold value of total velocity below which the texture becomes finer with increasing total velocity, and above which foam texture does not change significantly. The distinction between the two regions of plug flow ((A) and (C)) and segregated flow ((B) and (D)) can also be described by using the observation of the effluent history, which is, gas and liquid fractions at the effluent are roughly the same as those at the injection port during plug flow, while liquid fraction at the effluent is much higher than that at the injection port during segregated flow. The fact that the steady-state pressure drop in the low-quality regime is insensitive to liquid velocity (or, the pressure contours are relatively horizontal
in the low-quality regime, equivalently) can be explained by “lubricating effect” or “drainage effect” (Weissman and Clavert, 1967; Joseph et al., 1999; Briceno and Joseph, 2003) – in case of plug flow, the increase in liquid velocity causes foam films to be thickening, which in turn reduces the friction between bubbles or the friction between bubbles and walls without affecting the pressure drop significantly (i.e., lubricating effect); on the other hand, in case of segregated flow, the increase in liquid velocity causes the level of liquid accumulated at the bottom to move upward, which results in the increase of liquid fraction in pipe without affecting the pressure drop significantly (i.e., drainage effect).

![Figure 4.28: A schematic of characterization of foam flow in horizontal pipes based on foam texture, flow pattern, and pressure response.](image-url)
Further about the drainage effect in segregated flow, it is observed that the thickness of the lower liquid layer increases with increasing liquid velocity at fixed gas velocity, as sketched in the three figures at the bottom of Fig. 4.28. In contrast, an increase in gas velocity at fixed liquid velocity leads to a reduction in the thickness of the lower liquid layer, ultimately getting rid of liquid layer accumulated at the bottom of the pipe beyond a certain value of gas velocity. This behavior that the fraction of gas and liquid phases accumulated in the pipe is constantly changing depending on injection quality and total injection velocity (and thus foam texture) is very similar to the relative permeability effect which describes why the low-quality regime of strong foams in porous media is relatively insensitive to liquid velocity as investigated by Rossen and Wang (1999) and implied by others (Osterloh and Jante, 1992; Alvarez et al., 2001; Dholkawala et al., 2007; Kam, 2008).

Fig. 4.28 also explains why the two regimes have different sensitivities to gas and liquid velocities. As shown in the contour plots, the contours in the high-quality regime have finite slopes because an increase in liquid velocity (which results in increasing foam-slug section) can be compensated by an increase in gas velocity (which results in increasing free-gas section). Put it differently, any change in injection conditions which makes foams drier is expected to lengthen the free-gas section, causing a reduction in the pressure drop, while any change in injection conditions which makes foams wetter is expected to elongate the fine-textured-foam section, causing an increase in the pressure drop. The contours in the low-quality regime have almost negligible slopes because an additional supply of liquid is spent in thickening liquid films at the wall or between bubbles (if plug flow) and/or lower liquid layer (if segregated flow) such that the increase in liquid velocity does not contribute to the change in the steady-state pressure.
response significantly. This pressure response relatively less sensitive to liquid velocity in the low-quality regime is consistent with self-lubricating effect.

Fig. 4.29 shows the effect of surfactant concentration (0.1, 0.5, and 5 wt% of Aquet-944) at two liquid velocities of 0.015 and 0.030 ft/s ($Q_w = 20$ and 40 cm$^3$/min, respectively). As expected, the flow experiments at higher surfactant concentration shows more stable foams with finer foam texture in general. Therefore, higher surfactant concentration results in expanding low-quality regime (or, shrinking high-quality regime equivalently) and, more importantly, a growing plug-flow region and a shrinking segregated-flow region.

![Graph showing effect of surfactant concentration on liquid velocity](image)

**Figure 4.29(a):** Effect of surfactant concentration by using 0.1, 0.5, and 5 wt% of Aquet-944 at the same liquid velocity of 0.015 ft/s ($Q_w = 20$ cm$^3$/min).
Fig. 4.29(b): Effect of surfactant concentration by using 0.1, 0.5, and 5 wt% of Aquet-944 at the same liquid velocity of 0.030 ft/s ($Q_w = 40$ cm$^3$/min).

Fig. 4.30 depicts how this two-flow-regime concept can improve modeling and simulation of foam-assisted underbalanced drilling in which the process experiences a significant change in pressure and temperature in addition to the influx of foreign fluids into the wellbore. For example, during the flow of foams along drill pipe and annulus, gas phase expands and shrinks considerably, forcing the flow conditions to move across the $f^*_g$ boundary between the two regimes. In addition, the intrusion of formation fluids can play a significant role too: formation brine may dilute the surfactant concentration; reservoir oils entering the bottom hole can destabilize the foam mixture, and reduce effective foam viscosity and solid carrying capability; and gas influx may increase the fraction of gas phase in the mixture along the annulus. All these events tend to shift the locus of $f^*_g$ downward, increasing the possibility of the
system moving into the high-quality regime. Also the fact that the locus of $f^*_g$ is curved concavely means that it is easier to obtain the high-quality regime as liquid velocity increases, which is obviously a factor to be considered in field applications.

Fig. 4.30 also provides good insights into applications like foam fracturing treatments in which maximizing the capability of solid transport is the key to the process. Because it is the interface between gas and liquid which effectively captures and mobilizes solids, the optimum injection condition should be maintained such that the flow of foam mixture stays within the plug-flow region (cf., Fig. 4.28). The plug flow regime, where the maximum foam apparent viscosity (corresponding to the maximum pressure drop) occurs, helps solid transportation. An increase in interfacial area and viscosity avoids the slippage of the particles and improves the carrying capacity of the cuttings (Abbott, 1974; Okpobiri and Ikoku, 1986). It is believed that this optimum condition can be pre-determined from laboratory flow experiments similar to those shown in this study prior to field applications. Any deviation from the plug-flow region is expected to undermine the ability of foams as a solid carrier. How to implement two-flow regime concept developed in this study is obviously a very field-specific and application-specific task which can be considered as a future study.
Figure 4.30: A schematic showing the implication of two-flow regime on underbalanced drilling processes.
CHAPTER 5

RESULTS AND DISCUSSIONS: FOAM FLOW IN INCLINED PIPES

This chapter focuses on the effect of different flow directions, especially at the following five inclination angles: horizontal (i.e., inclination angle = 0°), 45° upward, 90° upward, 45° downward, and 90° downward, which are named Base Case, Case 1, Case 2, Case 3, and Case 4, respectively in this chapter (note that the Base Case in Chapter 5 is not the same as the Base Case in Chapter 4). One more case, called Case 5, is conducted to look more closely the transition from segregated flow pattern to plug flow pattern at low gas rates at 45° upward inclination. These six cases are shown in Table 5.1. Other than the inclination angles varied, all other experimental conditions are kept the same, including 0.5 wt% Cedepal FA-406 and 0.38/0.5-inches ID/OD Nylon-6 pipes.

Table 5.1: List of Six Cases at Different Inclination Angles.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Pipe size and Material</th>
<th>Surfactant Type and Concentration</th>
<th>Inclination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>ID/OD 0.38”/0.5” Nylon 6</td>
<td>Cedepal FA-406, 0.5 wt%</td>
<td>0° Horizontal</td>
</tr>
<tr>
<td>1</td>
<td>ID/OD 0.38”/0.5” Nylon 6</td>
<td>Cedepal FA-406, 0.5 wt%</td>
<td>45° UP</td>
</tr>
<tr>
<td>2</td>
<td>ID/OD 0.38”/0.5” Nylon 6</td>
<td>Cedepal FA-406, 0.5 wt%</td>
<td>90° UP</td>
</tr>
<tr>
<td>3</td>
<td>ID/OD 0.38”/0.5” Nylon 6</td>
<td>Cedepal FA-406, 0.5 wt%</td>
<td>45° DOWN</td>
</tr>
<tr>
<td>4</td>
<td>ID/OD 0.38”/0.5” Nylon 6</td>
<td>Cedepal FA-406, 0.5 wt%</td>
<td>90° DOWN</td>
</tr>
<tr>
<td>5</td>
<td>ID/OD 0.38”/0.5” Nylon 6</td>
<td>Cedepal FA-406, 0.5 wt%</td>
<td>45° UP</td>
</tr>
</tbody>
</table>

5.1 Base Case (Inclination 0°)

Figs. 5.1(a) through 5.1(d) show the base-case experiments at the liquid injection rate (Q_w) of 20, 40, 60, and 80 cm³/min. In each experiment, the gas injection rate (Q_g) varies from 200 to 5000 cm³/min step by step, first in increasing order followed by decreasing order.

The results of sectional pressure drops from transducers A through H show a few interesting behaviors: (1) the plots are in general symmetric, meaning that there is no hysteresis
involved with the change in gas flow rates; (2) there is a threshold value of gas flow rate, below which the steady-state sectional pressure drop increases with gas rate, but above which the steady-state sectional pressure drop decreases with gas rate, as well demonstrated in Figs. 5.1(a) and 5.1(b); and (3) the pressure data collected during the experiments look relatively stable below the threshold gas flow rate and relatively scattered above the threshold gas flow rate. These effects described in (2) and (3) are consistent with previous observations in the horizontal-flow experiments (e.g. Fig. 4.28) in which the high-quality regime is characterized by alternating free gas and fine-textured foams (called “slug flow pattern”) and the low-quality regime is characterized by either fine-textured foam flow (called “plug flow pattern”) or segregated layered flow between foams and liquid (called “segregated flow pattern”).

Figure 5.1(a): Pressure response of the Base Case (Inclination 0°) at pressure ports A through H with liquid injection rate 20 cm³/min.
Figure 5.1(b): Pressure response of the Base Case (Inclination 0°) at pressure ports A through H with liquid injection rate 40 cm³/min.

Figure 5.1(c): Pressure response of the Base Case (Inclination 0°) at pressure ports A through H with liquid injection rate 60 cm³/min.
Figure 5.1(d): Pressure response of the Base Case (Inclination 0°) at pressure ports A through H with liquid injection rate 80 cm³/min.

The steady-state pressure values read from Figs. 5.1(a) through 5.1(d) can be used to construct a plot of pressure drop (ΔP) vs. gas rate (Q_g) (or, shear stress (τ_w) vs. shear rate (µ_w)) as shown in Fig. 5.2, and a plot of pressure drop (ΔP) vs. foam quality (f_g) (or, apparent foam viscosity (µ_app) vs. shear rate (γ_w)) as shown in Fig. 5.3. These plots can be drawn in a form of pressure or apparent viscosity contours as shown in Fig. 5.4. These figures clearly indicate that there exist two very distinct foam flow regimes which are separated by a threshold foam quality value, f_g^*. It should be noted that the pressure-drop values reported here are from pressure transducers B though G because of possible entry and exit effect, and the gas rates in Figs. 5.2 and 5.3 are values adjusted at the average pressure within the pipe (i.e., (P_B+P_G)/2).
Figure 5.2: The steady-state pressure drops over 8.52 ft. pipe length at various gas rates, or the steady-state shear stress at various shear rates at fixed liquid velocity (Base Case) with inclination angle 0°.

Figure 5.3: The steady-state pressure drops over 8.52 ft. pipe length at various foam qualities or apparent foam viscosity at various shear rates (Base Case with inclination angle 0°).
5.2 Effect of Inclination on Two Flow Regimes (Case 1 through Case 4)

Similar flow experiments were conducted at different inclination angles. They are named Case 1 through Case 4 for 45° upward, 90° upward, 45° downward, and 90° downward, respectively, of which the steady-state pressure drops and apparent foam viscosities are presented as shown in Figs. 5.4 through 5.8. Details of these pressure data during experiments in Case 1 through Case 5 are included in Appendix D.

The results from these figures show that the overall shapes of pressure and viscosity contours are not noticeably affected by inclination angles. A closer look at the contour plots in Figs. 5.5 through 5.8 shows that the maximum apparent viscosity values are around 300 cp, which indicates that the whole process is dominated by viscous force rather than gravitational force once fine-textured foams are formed.
Figure 5.5: Pressure and apparent-viscosity contours for Case 1 (Inclination 45° Upward): (a) pressure values in psi over 8.52 ft. length and (b) apparent-viscosity in cp calculated from pressure data.

Figure 5.6: Pressure and apparent-viscosity contours for Case 2 (Inclination 90° Upward): (a) pressure values in psi over 8.52 ft. length and (b) apparent-viscosity in cp calculated from pressure data.
Figure 5.7: Pressure and apparent-viscosity contours for Case 3 (Inclination 45° Downward): (a) pressure values in psi over 8.52 ft. length and (b) apparent-viscosity in cp calculated from pressure data.

Figure 5.8: Pressure and apparent-viscosity contours for Case 4 (Inclination 90° Downward): (a) pressure values in psi over 8.52 ft. length and (b) apparent-viscosity in cp calculated from pressure data.
This implies that for foam rheology to be strongly affected by inclination angle, the region of interest should be where the apparent foam viscosity is relatively low. This in turn implies that the effect of inclination is more relevant to a lower foam quality in the low-quality regime, especially near or below the transition from segregated flow to plug flow pattern, which is discussed more in the following section.

5.3 Transition From Segregated To Plug Flow Pattern (Case 5)

A series of experiments are followed in order to observe the pattern of foam flow in pipes. The results are shown in Figs. 5.9, 5.10, and 5.11 for horizontal, 45° upward and 45° downward experiments, respectively.

As visualized from the flow experiments in horizontal pipes, three different flow patterns are also observed in the new system in case of horizontal flow experiments: slug flow pattern in the high-quality regime where the pressure contours have some finite slopes (cf. Figs. 5.4 through 5.8); and either plug flow or segregated flow in the low-quality regime where the pressure contours are relatively flat (cf. Figs. 5.4 through 5.8).

The same visualization experiments are shown in Figs. 5.10 and 5.11 at 45° upward and 45° downward inclination angles. There are a few important aspects observed which should be noted as follows: (1) the three flow patterns observed in horizontal flow (i.e., slug, plug, and segregated flow patterns) are still present in a wide range of inclination angles (all the way from 90° upward to 90° downward, although results are shown only for 45° upward and 45° downward); (2) for upward flow (e.g. Fig. 5.10), if the flow condition falls within the segregated flow pattern in the horizontal flow, the system repeats two states of (a) the layered flow of foam and liquid, both flowing together upward and (b) the upper foam layer flowing upward but the lower liquid layer flowing downward (the downward motion of liquid is accompanied by the
Figure 5.9: Flow patterns observed in Base Case (Inclination 0°)

accumulation of liquid at a certain location first, then the liquid moving downward due to gravity is taken up by the rising foams, the liquid either moves together with the foams as a distinct layer or help create fine textured foams); and (3) for downward flow (e.g. Fig. 5.11), if the flow condition falls within the segregated flow pattern in the horizontal flow, the lower liquid layer runs fast and the upper foam layer runs slow as the inclination becomes steeper (because of the liquid running faster, the liquid layer is thinner during downward flow compared to that during horizontal flow).

These observations in upward and downward flow directions show that the formation of fine-textured foams, which is required for the transition from segregated flow pattern to plug flow pattern, is more favored for upward flow due to the relatively higher liquid fraction caused
Figure 5.10: Flow patterns observed in Case 1 (Inclination 45° Upward)

Figure 5.11: Flow patterns observed in Case 3 (Inclination 45° Downward)
by sporadic downward flows of accumulated liquid, but less favored for downward flow due to
the relatively lower liquid fraction caused by rapid downward liquid movement. This concept is
depicted in Fig. 5.12 in which the envelope that separates segregated flow pattern from plug flow
pattern becomes smaller as the inclination angle changes from 90° downward to horizontal and
eventually to 90° upward. This means that (1) in experiments varying gas rate at fixed liquid rate,
the threshold gas rate at which the transition from segregated flow to plug flow takes place is
lower (cf. vertical line (A) in Fig. 5.12) and (2) in experiments varying total gas and liquid rate at
fixed foam quality, the threshold total rate at which the transition from segregated flow to plug
flow takes place is also lower (cf. line (B) in Fig. 5.12), as the inclination angle decreases from
90° downward to 90° upward. It should be noted that the shape of the envelope appears to be
concave in general because an increase in liquid rate at the same gas rate tends to create fine-
textured foam more easily.

Figure 5.12: Boundaries separating three different patterns: the transition from segregated
to plug flow is significantly affected by inclination angles.
It should be emphasized that in many foam applications such as foam drilling and fracturing, the large interfacial area between gas and liquid is highly desirable for the purpose of maximizing cutting transport and proppant delivery. Therefore, the fact that the boundary between segregated flow and plug flow is sensitive to the changes in inclination angle (cf. Fig. 5.16) implies that the inclination angle should be an important parameter in field treatments.

5.4 Implication of Results to Pressure Contours at Different Inclination Angles

The results in Figs. 5.9 through 5.11 indicate that the pressure contours obtained from horizontal flow experiments are still applicable to the case of other inclination angles, as long as the flow patterns fall into either slug flow in the high-quality regime or plug flow in the low-quality regime. On the other hand, if the flow pattern falls within segregated flow pattern in the low-quality regime, the steady-state pressure contours are sensitive to the inclination angles. The major distinction between these two cases is that the former is governed by viscous force, while the latter is governed by gravitational force.

Fig. 5.13 shows a schematic figure with the nature of these inclination-angle-specific pressure drops. In horizontal flow with no gravity effect, the steady-state pressure drop increases with gas velocity showing a slight shear-thinning behavior (e.g. Figs. 5.1 and 5.2). In case of upward flow, the pressure drop first decreases with gas velocity because the flow is segregated (i.e., the gravitational force is dominant); then increases with gas velocity and merges with the locus of horizontal flow because the viscous force becomes dominant. In case of downward flow, the gravity is acting in the opposite way such that the pressure drops are even lower than those in horizontal flow before merging into the plug flow pattern where the viscous force is dominant.
Figure 5.13: A schematic showing the transition from segregated flow to plug flow at different inclination angles.
CHAPTER 6

FURTHER DISCUSSIONS ON TWO FOAM-FLOW REGIMES

This chapter addresses issues relevant to the two foam-flow regime concept, through the following four major sections: i) section 6.1 to describe the comparative evaluation of two flow regime concept with previous foam modeling efforts and experimental data; ii) section 6.2 to compare the flow regime map developed in this study with those in existing multiphase flow studies in the literature; iii) section 6.3 to investigate implication of two flow regimes in foam drilling hydraulics; and iv) section 6.4 to show the statistical analysis of fluctuations in pressure measurement in both high-quality and low-quality regimes.

6.1 Comparison with Existing Foam Models and Experimental Data

A number of foam models, mostly based on either theoretical description of foam rheology under shear flow or laboratory foam flow experimental data, are available in the literature. Among many, this study selects six previous studies: three foam modeling studies from Beyer et al. (1972), Sanghani and Ikoku (1983), and Reidenbach et al. (1986); and three foam experimental studies from Sanghani and Ikoku (1983), Briceno and Joseph (2003), and Guzman et al. (2005). The outcomes of these studies are plotted in the form of pressure contours or foam-viscosity contours as a function of injection velocities in order to make a comparison with the two flow regime concept presented in this study. Details of these six studies can be found in the original papers and hence are not repeated here. The comparison shows that the use of two flow regime concept has not been established before, therefore further modeling efforts should be made accordingly for more reliable foam field applications.
6.1.1 Beyer et al.’s Model

Beyer et al. (1972) formulated the equations for steady-state flow of aqueous foams in circular pipes from laboratory- and pilot-scale experimental data. The laboratory-scale experiments were performed with a 0.622 inch internal diameter pipe, and the pressure drop was measured along a 4 ft. section of pipe. The range of liquid volume fraction was 0 to 0.04, with 0.06 - 0.6 wt% Textilana SAT surfactant solutions. For total injection velocities from 0.5 to 4 ft/sec, the measured pressure was typically less than 56 psig. The pilot-scale experiments were performed on three 100 ft sections of horizontal pipes with internal diameters of 0.546, 0.742, and 0.957 inches. Liquid volume fraction was varied from 0.02 to 0.25 with 0.2 wt% Chevron WF-100 surfactant. The typical pressure range was from 50 to 860 psig at total velocities from 1.2 to 16.4 ft/sec. These experimental data were matched by a Bingham plastic model, and its plastic viscosity was expressed based on liquid volume fraction at 0.02 - 0.1 and 0.1 - 0.25.

Beyer et al.’s model correlates slip velocity with liquid volume fraction and wall shear stress. They concluded that foam quality principally controls foam behavior, and stated the equation considering wall slippage and fluidity component as follows:

\[ \mu_o = \frac{1}{(7200 \times LFV + 267)} \], for liquid volume fraction from 0.02 to 0.1  

\[ \mu_o = \frac{1}{(2533 \times LFV + 733)} \], for liquid volume fraction from 0.1 to 0.2  

Where, \( \mu_o \) is the Bingham plastic viscosity, and LVF presents liquid volume fraction of the foam.
Fig. 6.1 shows plots of foam viscosity based on equations (6-1) and (6-2) (Fig. 6.1 (a)) and viscosity contours (Fig. 6.1 (b)). The contours seem to show the behavior of low-quality regime, but with finite slopes.

![Figure 6.1: Beyer et al.'s model: (a) foam viscosity vs. foam quality and (b) viscosity contours.](image)

6.1.2 Sanghani and Ikoku’s Model

Sanghani and Ikoku (1983) conducted foam flow experiments in the annulus with drill pipe (outer diameter 1.5 inch) and casing (diameter 4.5 inch), both about 28.5 ft long. The range of foam quality tested was from 0.65 to 0.95, and the shear rates ranged from 150 to 1000 sec⁻¹. The calculated foam effective viscosity was in the range of 60 to 500 cp. They formulated empirical equations for the effective foam viscosity on the basis of foam quality by using experimental data. They correlated foam viscosity ($\mu_e$) with the power law model parameters $K$ and $n$ as follows.

$$\mu_e = K \left( \frac{2n+1}{3n} \right)^n \left( \frac{12\nu_f}{D_H} \right)^{n-1}$$

(6-3)

$$K = -0.15626 + 56.147\Gamma - 312.77\Gamma^2 + 576.65\Gamma^3 + 63.96\Gamma^4 - 960.46\Gamma^5 -$$

80
\[ 154.68 \Gamma^6 + 1670.2 \Gamma^7 - 937.88 \Gamma^8 \]

\[ n = 0.095932 + 2.365 \Gamma - 10.467 \Gamma^2 + 12.955 \Gamma^3 + 14.467 \Gamma^4 - 39.673 \Gamma^5 + 20.625 \Gamma^6 \]

where, \( v_f \) is foam velocity, \( D_H \) is hydraulic diameter, and \( \Gamma \) is foam quality.

Fig. 6.2 shows plots of foam viscosity based on equations (6-3) through (6-5) (Fig. 6.2 (a)) and viscosity contours (Fig. 6.1 (b)). This model implies presence of two flow regimes, the results show contours with mostly horizontal slopes, but with foam viscosity decreasing with increasing foam quality similar to the high-quality regime.

![Figure 6.2: Sanghani and Ikoku’s model: (a) foam viscosity vs. foam quality and (b) viscosity contours.](image)

### 6.1.3 Reidenbach et al.’s Model

Reidenbach et al. (1986) proposed a mathematical model based on the experimental data. Their experiments were performed with 0.5 wt% of an anionic surfactant, together with 0 to 0.48 wt% of hydroxyl propyl guar (HPG) added as a gelling agent. The pressure drop was measured across a 10 ft. pipe section with internal diameter of 0.305 inch. Two separate equations were developed for foam quality (i) less than 60% and (ii) more than 60 %. The apparent yield point
(τ<sub>yp</sub>), consistency index (K), and behavior index (n) were computed with least-square regression for a fixed foam quality. The apparent viscosity (μ<sub>a</sub>) is given by the following equations:

\[
\mu_a = \tau_{yp} \left( \frac{8v}{d} \right)^{-1} + K \left( \frac{8v}{d} \right)^{n-1}, \quad \text{.................................................} \quad (6-6)
\]

where, \( \tau_{yp} = C_1 \Gamma \), for \( \Gamma < 0.6 \) and \( \tau_{yp} = C_2 e^{C_3 \Gamma} \), for \( \Gamma > 0.6 \), ............................... (6-7)

and

\[
K = K_{\text{liquid}} \times e^{(C_1 \Gamma + C_2 \Gamma^2)}, \quad \text{.................................................} \quad (6-8)
\]

where, \( \Gamma \) is foam quality, \( d \) is internal diameter of pipe, \( v \) is bulk velocity and \( K_{\text{liquid}} \) is consistency index for liquid phase. The constants \( C_1, C_2 \) and \( C_3 \) depend on surfactant concentration, foam texture, and physical properties of mixture and conduit.

Fig. 6.3 shows plots of foam viscosity based on equations (6-6) through (6-8) (Fig. 6.3 (a)) and viscosity contours (Fig. 6.3 (b)). Although, this model implies the presence of two flow regimes, the contours look quite different from what was observed in this study.

![Figure 6.3](image)

**Figure 6.3:** Reidenbach et al.’s model: (a) foam viscosity vs. foam quality and (b) viscosity contours.
6.1.4 Sanghani and Ikoku’s Data

Sanghani and Ikoku’s model as described in section 6.1.2 was based on their experimental data. Fig. 6.4 shows their raw pressure data plotted in the way this study presented by using pressure contours. The general trend shows contours with finite slopes similar to the high-quality regime observed in this study.

Figure 6.4: Pressure contour map developed using Sanghani and Ikoku data.

6.1.5 Briceno and Joseph’s Data

Briceno and Joseph (2003) conducted experiments for foam flow through plexi-glass pipe with 0.625 inch inner diameter and 4 ft length at 0.6 wt% surfactant concentration. Their experimental data can be plotted as shown in Fig. 6.5. The pressure contours are almost horizontal similar to the behavior of the low-quality regime observed in this study.
6.1.6 Guzman et al.’s Data

Guzman et al. (2005) conducted experiments with internal pipe diameter 2 inch and pipe length 56 ft at 0.2 vol.% surfactant concentration. Their data, as shown in Fig. 6.6, do not reflect any of the two flow regimes. It might be because of their experimental conditions, very dry foams at relatively high injection velocities, which might fall in the annular- or mist-flow region where gas forms a continuous phase with a discontinuous liquid phase.
Figure 6.6: Pressure contour map developed using Guzman et al.’s data.

6.2 Comparison of Flow Regime Maps

The use of flow regime maps has been popular, especially in petroleum production industry, to characterize different types of multiphase flow in vertical, horizontal, and inclined pipes. This section compares the range of experimental conditions in this study with the flow regime maps in the literature in order to provide an easier means for further analysis of foam flow. Three examples shown below illustrate that the flow regime maps for multiphase flow in the absence of surfactant cannot capture the flow behavior observed during foam flow.
6.2.1 Taitel and Dukler’s Map

Taitel and Dukler (1976) developed a flow regime map for air-water system. The transition between different flow regimes are presented as a function of superficial gas and liquid velocities, as shown in Fig. 6.7(a). The range of experimental conditions of this study is superimposed by using a small rectangular box shown near the origin, implying that, with no surfactant added, all experimental data would have fallen into the segregated (or stratified) flow. Fig. 6.7(b) shows how experimental data collected from the base case in Chapter 4 (Fig. 4.7(a)) can be populated in the rectangular box for further comparison.

![Flow Regime Map](image)

**Figure 6.7:** Comparison with Taitel and Dukler’s flow regime map (1976): (a) the range of experimental conditions of this study and (b) data points from the contour map in Fig. 4.7(a).

6.2.2 Baker’s Map

Baker (1954) developed a flow regime map for air-water flow with gas mass flux and water mass flux, by incorporating phase properties such as density, viscosity, and surface
tension. Figs. 6.8(a) and 6.8(b) show the range of this experimental study and the comparison with flow regime map in Fig. 4.7(a). Again, all experimental conditions in this study would have fallen into the stratified flow with no surfactant present.

Figure 6.8: Comparison with Baker’s flow regime map (1954): (a) the range of experimental conditions of this study and (b) data points from the contour map in Fig. 4.7(a).

6.2.3 Beggs and Brill’s Map

Beggs and Brill developed a flow regime map based on Froude number and liquid fraction, as shown in Fig. 6.9(a). Similar to Figs. 6.7 and 6.8, Fig. 6.9(a) shows the range of experimental conditions super-imposed, and Fig. 6.9(b) shows the data points from Fig. 4.7(a). Again, the segregated-flow pattern is expected for all experimental conditions in the absence of surfactant.
Figure 6.9: Comparison with Beggs and Brill’s flow regime map (1973): (a) the range of experimental conditions of this study and (b) data points from the contour map in Fig. 4.7(a).
6.3 Implication of Two Flow Regimes in Foam Drilling Hydraulics

This section briefly describes how two flow regime concept can impact the current foam drilling hydraulics by using example calculations. Table 6.1 shows input parameters for this task. For simplicity, the system is assumed to be at isothermal condition with only two phases (gas and surfactant solution) present in a vertical well.

It is further assumed that the foams of interest are represented by Stepamform-1050 (Case 4 in chapter 4). Foam rheology extracted by experimental data is approximated by two empirical equations shown in Fig. 6.10, for high-quality and low-quality regimes. The value of $f_g^*$ is about 0.88.

Drilling hydraulics calculations along the annulus is similar to the pressure traverse calculation, which is further detailed as follows:

Table 6.1. Input Data for the Hydraulic Calculation Along the Annulus.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured Depth (ft)</td>
<td>10000</td>
<td>$\rho_L$, lbm/ft$^3$</td>
<td>62.4</td>
</tr>
<tr>
<td>Hole size (inch)</td>
<td>8.5</td>
<td>Mg (lbm/lbmol)</td>
<td>28.9</td>
</tr>
<tr>
<td>Drill Pipe OD (inch)</td>
<td>5</td>
<td>$q_L$ (gpm)</td>
<td>40</td>
</tr>
<tr>
<td>Drill Pipe ID (inch)</td>
<td>4.276</td>
<td>$q_g$ (scfm)</td>
<td>1200</td>
</tr>
<tr>
<td>$\mu_L$ (cp)</td>
<td>1</td>
<td>$P_{sur}$ psi</td>
<td>50</td>
</tr>
<tr>
<td>Specific Gravity ($\gamma_g$)</td>
<td>0.9723</td>
<td>Temperature (°R)</td>
<td>540</td>
</tr>
</tbody>
</table>
Step 1: Assume the value of wellbore (bottomhole) pressure.

Step 2: The gas rate at the wellbore is calculated by using gas rate at surface condition by applying the real gas law.

\[
\frac{P_1 V_1}{Z_1} = \frac{P_2 V_2}{Z_2}, \quad \text{.................................................................} \quad (6-9)
\]

The subscripts 1 and 2 indicate two different conditions. Subscript “1” indicates surface conditions which are given in Table 6.1, and subscript “2” refers to conditions at any location of interest in the wellbore. Therefore, the actual gas flow rate at wellbore \((q_{gWB})\), for example, is calculated by

\[
q_{gWB} = \frac{P_{\text{sur}} \times q_{\text{sur}} \times Z_{\text{WB}}}{P_{WB} \times Z_{\text{sur}}}, \quad \text{.................................................................} \quad (6-10)
\]

Where \(P_{\text{sur}}\), \(q_{\text{sur}}\), and \(Z_{\text{sur}}\) are the pressure, gas flow rate, and compressibility factor at surface conditions, and \(P_{WB}\), \(q_{WB}\), and \(Z_{WB}\) represent the pressure, gas flow rate, and compressibility factor at the wellbore condition.

Step 3: The superficial velocities of gas and liquid are calculated by using the cross-sectional area of the annulus, gas rate and liquid rate at the wellbore. Liquid phase is considered as an incompressible phase. The superficial gas velocity \((u_g)\) is given by

\[
u_g = \frac{q_g}{A}, \quad \text{.................................................................} \quad (6-11)
\]

The superficial liquid velocity \((u_w)\) is given by

\[
u_w = \frac{q_w}{A}, \quad \text{.................................................................} \quad (6-12)
\]
Step 4: Foam quality ($f_g$) is given by

$$f_g = \frac{u_g}{u_g + u_w}$$  

Step 5: Gas density ($\rho_g$) is calculated by

$$\rho_g = \frac{P \times y_g \times M_g}{Z \times R \times T}$$  

where $M_g$ is molecular weight of gas phase, $R$ is the universal gas law constant, $Z$ is compressibility factor, and $T$ is temperature of gas phase.

Step 6: Foam density ($\rho_f$) is calculated by

$$\rho_f = (\rho_g \times f_g) + (\rho_w \times (1 - f_g))$$  

where $\rho_w$ is liquid density.

Step 7: Apparent foam viscosity ($\mu_{app}$) is determined by following equations in Fig. 6.10.

![Figure 6.10: Apparent foam viscosity as function of foam quality for Case 4 Stepanform-1050, 0.1 wt.% concentration: (a) low-quality regime and (b) high-quality regime.](image)

- For foam quality below $f_g^*$, the equation is:
  $$y = 11.216e^{2.7624x}$$
  $$R^2 = 0.8702$$

- For foam quality above $f_g^*$, the equation is:
  $$y = 3819.8x^2 - 7762.5x + 3942.9$$
  $$R^2 = 0.9349$$
For foam quality below $f_g^*$,

$$
\mu_{app} = 11.216 e^{2.7624f_g} . \hspace{1cm} (6-16)
$$

For foam quality above $f_g^*$,

$$
\mu_{app} = 3819.8f_g^2 - 7762.5f_g + 3942.9 . \hspace{1cm} (6-17)
$$

Step 8: Foam velocity ($u_f$) is calculated by

$$
u_f = u_g + u_w. \hspace{1cm} (6-18)
$$

Step 9: Reynolds number is given by

$$
R_e = \frac{\rho_f u_f D_h}{\mu_{app}} \hspace{1cm} (6-19)
$$

where $D_h$ is the hydraulic radius (i.e., $D_h = \text{Casing ID} - \text{Drill pipe OD}$).

Step 10: Friction factor in the annulus ($f$) is then decided as follows:

For $Re < 2100$

$$
f = \frac{64}{Re} \left( \frac{(1-k)^2}{1-k^4 \frac{1-k^2}{\ln \frac{D_h}{D_i}}} \right) \hspace{1cm} (6-20)
$$

and for $Re > 2100$

$$
f = \left[ f_f \left( \frac{F_p}{F_{CA}} \right)^{0.45} \exp \left[-\left(\text{Re}-3000\right)/10^6\right] \right]^{-0.5} \hspace{1cm} (6-21)
$$

where the geometry parameters, $F_p$ and $F_{CA}$, are defined by

$$
F_p = \frac{16}{Re} \hspace{1cm} (6-22)
$$
\[ F_{CA} = \frac{(1-k)^2}{1-k^4} \frac{1-k^2}{1-k^2} \frac{1}{kn_g}, \]  

(6-23)

and \( k \) is the ratio of drill pipe outer diameter to casing inner diameter.

Step 12: Frictional pressure gradient \( \left( \frac{dp}{dt} \right)_f \) is given by

\[ \left( \frac{dp}{dt} \right)_f = \frac{f \rho_f u_f^2}{D_h}, \]  

(6-24)

Step 13: Hydrostatic pressure gradient \( \left( \frac{dp}{dt} \right)_H \) is given by

\[ \left( \frac{dp}{dt} \right)_H = \rho_f g, \]  

(6-25)

The total pressure gradient is the summation of these two, neglecting acceleration pressure loss.

The annulus is divided into 21 segments, and Step 1-13 are applied for drilling hydraulics calculations. The procedure is iterated until the calculated surface pressure matches with the input surface pressure, assuming different values of bottomhole pressure.

Fig. 6.11 shows the results from this foam drilling hydraulics calculation in terms of pressure, foam quality, apparent foam viscosity, total velocity, hydrostatic pressure gradient, and friction pressure gradient along the annulus. It is clearly shown the presence of two flow regimes plays a significant role and thus should not be overlooked.
Figure 6.11: Results of example foam drilling hydraulics calculations: (a) pressure (b) foam quality (c) foam viscosity (d) total velocity (e) hydrostatic pressure gradient, and (f) frictional pressure gradient.
6.4 Statistical Analysis

In all experiments in Chapter 4 and Chapter 5, the pressure response in the low-quality regime is shown to be relatively stable, while the pressure response in the high-quality regime is shown to be relatively fluctuating. This section revisits the plots with FA-406 at 0.5, 0.1, and 5 wt% concentrations to quantify the level of oscillation associated with pressure data. The quantitative statistical analysis shown in Figs. 6.12 through 14 is made in terms of the average and the standard deviation of the raw pressure data. Irrespective of the average values, the standard deviation is relatively small for foams in the low-quality regime, and large for foams in the high-quality regime. This quantitative analysis is believed to guide the determination of the flow regimes without biased opinions, if needed.

Figure 6.12: Statistical analysis of Base Case (0.5 wt% FA-406) experiments.
Figure 6.13: Statistical analysis of Case 1 (0.1 wt% FA-406) experiments.

Figure 6.14: Statistical analysis of Case 2 (5.0 wt% FA-406) experiments.
CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

This chapter consists of major conclusions and recommendations from this study.

7.1 Conclusions

The experimental study on foam flow in horizontal pipes (Chapter 4) can be summarized with the following major conclusions.

1. The presence of two-flow regimes observed and conjectured by the pressure data in the previous study was identified and confirmed by visualization experiments in this study: the high-quality regime with a relatively higher gas fraction (i.e., \( f_g > f_g^* \)) was characterized by fine-textured foams alternating with free gas (or, very coarse-textured foams if not), exhibiting slug flow; and the low-quality regime with a relatively lower gas fraction (i.e., \( f_g < f_g^* \)) was characterized by a stable flow of homogeneous foams, exhibiting either segregated or plug flow. The two regimes could be mapped out in a form of contour plot by using the resulting steady-state pressure drops or apparent foam viscosities. The boundary between the two flow regimes was expressed by a concave locus of \( f_g^* \) which is affected by different experimental conditions related to foam stability.

2. For foams in the high-quality regime, the alternation of fine-textured foams with free gas led to inherently unstable and oscillating pressure responses. Visualization experiments further demonstrated that within the high-quality regime, (i) an increase in gas velocity at the same liquid velocity elongated the size of free-gas section and reduced the size of foam-slug section, leading to lower steady-state pressure drop and (2) an increase in liquid velocity at the same gas velocity elongated the size of foam-slug section and shortened the size of free-gas section,
leading to a higher steady-state pressure drop. This implies that any change which makes the flow drier in the high-quality regime results in a longer free-gas section and a shorter foam-slug section, eventually leading to a lower pressure drop. Therefore, the high-quality regime can be said to be governed by the bubble-coalescence mechanism.

3. For foams in the low-quality regime, the uniform and homogeneous nature of foam flow led to stable pressure responses. In general, plug flow was observed at higher total velocities, whereas segregated flow was observed at lower total velocities. It was visualized from the experiments that (i) in segregated flow, as total velocities increased, foam texture became finer and the upper foam layer grew thicker, essentially making a transition to plug flow, and (ii) in plug flow, there was a threshold value of total injection velocity, below which foam texture became finer with increasing velocity, and above which foam texture did not change noticeably maintaining the steady-state texture. The lower liquid layer and the upper foam layer traveled at different velocities during segregated flow, typically with liquid production rate prevailing over gas production rate at the effluent, whereas bulky homogeneous foams flowed all together during plug flow with a thin liquid layer at the wall causing lubricating effect. The transition from segregated flow to plug flow, and further refinement of foam texture in the plug-flow region imply that foam rheology in the low-quality regime is governed by the bubble-creation mechanism.

4. As shown in the contour plots, a monotonic increase in gas velocity at fixed liquid velocity resulted in increasing steady-state pressure drops in the low-quality regime (i.e., $f_g$ up to $f_g^*$), but decreasing steady-state pressure drops in the high-quality regime (i.e., $f_g$ beyond $f_g^*$). This transition around $f_g^*$ based on the pressure data was consistent with that based on the visualization experiments, which is, the velocity condition at which the maximum pressure drop
occurred roughly coincided with the velocity condition at which the free-gas section started to appear near $f_g^*$. The texture of foam slug in the high-quality regime was comparable to the texture of fully developed foams in the plug-flow region in the low-quality regime, however.

5. Experimental results showed that $f_g^*$ that separated two flow regimes was not a fixed value. Rather, the magnitude of $f_g^*$ was sensitive to the experimental conditions which affected foam stability. It was observed that a reduction in surfactant concentration and/or the use of a poor foamer lowered $f_g^*$ and stretched the high-quality regime. This happens because the maximum foam texture that can be obtained from low surfactant concentrations or poor foamers is typically smaller than the maximum foam texture at higher surfactant concentrations or good foamers.

6. Visualization experiments describe why the pressure contours in the two flow regimes have different slopes, or why the steady-state pressure drops have different sensitivity to gas or liquid velocities: (i) in case of low-quality regime, the pressure contours are almost horizontal because an additional amount of liquid injected is consumed to increase the cross-sectional area open to liquid phase, if segregated flow, or to thicken the liquid film at the pipe wall, if plug flow (which is consistent with drainage and lubricating effects in earlier studies). On the other hand, the pressure contours are sensitive to gas velocity, because an increase in gas velocity results in increasing shear stress to make bubble size smaller, and drier foams tend to have a higher level of frictions between bubbles during shear flow; and (2) in case of high-quality regime, the pressure contours have finite slopes reflecting the fact that the steady-state pressure drop is influenced by both gas and liquid velocities. Any changes that cause the size of foam-slug section longer and the size of free-gas section shorter (i.e., by increasing liquid velocity or decreasing gas velocity) make the steady-state pressure drop higher.
Foam flow experiments carried out at different inclination angles (Chapter 5) end up with the following conclusions:

7. Experimental results showed that there existed two foam flow regimes consistently at all different inclination angles tested, including $90^\circ$ upward, $45^\circ$ upward, horizontal ($0^\circ$), $45^\circ$ downward, and $90^\circ$ downward. The value of $f_g^*$, which separated the high-quality regime from the low-quality regimes, did not seem to be affected noticeably by inclination angles. As previous experiments in horizontal pipes in Chapter 4 observed, the high-quality regime was characterized by slug flow and the low-quality regime was characterized by either plug flow or segregated flow, irrespective of inclination angles.

8. Once foam flow exhibited either slug flow pattern in the high-quality regime or plug flow pattern in the low-quality regime, the rheology was dominated by viscous force due to relatively fine foam texture. When this occurred, the steady-state pressure contours were almost unaffected by inclination angles. On the other hand, once foam flow exhibited segregated flow pattern in the low-quality regime, the rheology was dominated by gravitational force and the steady-state pressure drops were sensitive to inclination angles.

9. The transition from segregated flow to plug flow, which is crucial in many foam applications, occurred at higher foam quality (if liquid rate is fixed) or at higher total injection velocity (if foam quality is fixed) as the inclination angle moved from $90^\circ$ upward, $45^\circ$ upward, horizontal ($0^\circ$), $45^\circ$ downward, and eventually to $90^\circ$ downward. This is because, when it came to the creation of fine-textured foams, a sporadic back flow of liquid phase resulted in a favorable condition in upward flow, and a rapid flow down of liquid phase resulted in an unfavorable condition.
7.2 Recommendations

Based on the results, discussions, and conclusions in this study, the following recommendations can be made:

1. The experimental data showing pressure profiles, bubble sizes, and flow patterns in this study were obtained from small-scale flow experiments. Therefore, it is not clear yet how the outcome presented in this study would be affected in a larger scale. Large field-scale experiments with pipe size (diameter and length) more relevant to field applications are required.

2. For foam applications in underbalanced drilling, the process allows formation fluids such as brine, oil, and natural gas to flow into the drilling hole, which eventually influence foam flow patterns and rheology. An experimental investigation should be performed to quantify these effects from foreign fluids.

3. For foam fracturing applications, it is common to add many different types of chemical additives as well as polymers (such as guarans and Xanthans) for improved viscosity. The characteristics of foam flow at these conditions should be carried out for optimum foam fracturing treatments.

4. The concept of two flow regimes and the changes in bubble size and bubble size distribution presented in a form of contour plots in this study have not been presented before. This implies that the current simulators with foam rheology in fracturing and underbalanced drilling do not reflect these new ideas. Modeling and simulation studies should be followed in order to understand the impact of these new findings.
REFERENCES


APPENDIX A

EFFECT OF SURFACTANT CONCENTRATION: CASE 1 AND CASE 2 IN CHAPTER 4

Appendix A presents a summary of pressure data collected during Case 1 and Case 2 experiments in Chapter 4. Note that Case 1 and Case 2 use surfactant concentration of 0.1 wt% and 5 wt%, respectively, to be compared with Base-Case surfactant concentration of 0.5 wt%. The surfactant formulation is Cedepal FA-406.

For Case 1 (Figs. A1(a) to A1(d)), gas injection rate was first raised from 100 to 4000 cm$^3$/min step by step, and then reduced back to 100 cm$^3$/min, while for Case 2 (Figs. A2(a) to A2(d)), gas injection rate was first raised from 100 to 5000 cm$^3$/min step by step, and then reduced back to 100 cm$^3$/min. Note that the injection flow rate of 100 cm$^3$/min corresponds to the superficial velocity of 0.083 ft/s or 0.0253 m/s.

Figure A1(a): Pressure response of Case 1 (0.1 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 20 cm$^3$/min.
Figure A1(b): Pressure response of Case 1 (0.1 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 40 cm$^3$/min.

Figure A1(c): Pressure response of Case 1 (0.1 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 60 cm$^3$/min.
Figure A1(d): Pressure response of Case 1 (0.1 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 80 cm³/min.

Figure A2(a): Pressure response of Case 2 (5.0 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 20 cm³/min.
Figure A2(b): Pressure response of Case 2 (5.0 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 40 cm³/min.

Figure A2(c): Pressure response of Case 2 (5.0 wt% FA-406, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 60 cm³/min.
Figure A2(d): Pressure response of Case 2 (5.0 wt% FA-406, 0.36/0.5" ID/OD stainless-steel pipe) at fixed liquid injection rate of 80 cm³/min.
APPENDIX B

EFFECT OF SURFACTANT FORMULATION: CASE 3 AND CASE 4 IN CHAPTER 4

Appendix B shows pressure data collected during Case 3 and Case 4 experiments in Chapter 4, during which two different surfactant concentrations of 0.5 wt% (Figs. B1(a) to B1(d)) and 0.1 wt% (Figs. B2(a) to B2(d)) are applied respectively. Surfactant formulation in both cases is Stepanform 1050, which is an anionic surfactant.

In all experiments for Case 3 and Case 4, gas injection rate was first raised from 100 to 4500 cm$^3$/min step by step, and then reduced back to 100 cm$^3$/min. Only for the liquid injection rate 80 cm$^3$/min in Case 3, gas rate was raised up to 5000 cm$^3$/min. Note that the injection flow rate of 100 cm$^3$/min corresponds to the superficial velocity of 0.083 ft/s or 0.0253 m/s.

![Figure B1(a): Pressure response of Case 3 (0.5 wt% Stepanform1050, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 20 cm$^3$/min.](image)

Figure B1(a): Pressure response of Case 3 (0.5 wt% Stepanform1050, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 20 cm$^3$/min.
Figure B1(b): Pressure response of Case 3 (0.5 wt% Stepanform1050, 0.36/0.5" ID/OD stainless-steel pipe) at fixed liquid injection rate of 40 cm³/min.

Figure B1(c): Pressure response of Case 3 (0.5 wt% Stepanform1050, 0.36/0.5" ID/OD stainless-steel pipe) at fixed liquid injection rate of 60 cm³/min.
Figure B1(d): Pressure response of Case 3 (0.5 wt% Stepanform 1050, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 80 cm³/min.

Figure B2(a): Pressure response of Case 4 (0.1 wt% Stepanform 1050, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 20 cm³/min.
Figure B2(b): Pressure response of Case 4 (0.1 wt% Stepanform1050, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 40 cm³/min.

Figure B2(c): Pressure response of Case 4 (0.1 wt% Stepanform1050, 0.36/0.5” ID/OD stainless-steel pipe) at fixed liquid injection rate of 60 cm³/min.
Figure B2(d): Pressure response of Case 4 (0.1 wt% Stepanform1050, 0.36/0.5" ID/OD stainless-steel pipe) at fixed liquid injection rate of 80 cm³/min.
APPENDIX C

VISUALIZATION EXPERIMENTS THROUGH NYLON 6 TRANSPARENT PIPE: CASE 5 – CASE 8 IN CHAPTER 4

Appendix C shows the pressure data from the experiments using nylon-6 transparent pipe. Case 5 (Figs. C1(a) to C1(d)) is with surfactant Cedepal FA-406 (0.5 wt%) and Case 6 (Figs. C2(a) to C2(d)), Case 7 (Figs. C3(a) to C3(d)), and Case 8 (Figs. C4(a) to C4(d)) are with surfactant Aquet-944 at 5.0 wt%, 0.5 wt%, and 0.1 wt% concentrations, respectively. Note that the injection flow rate of 100 cm³/min corresponds to the superficial velocity of 0.0747 ft/s or 0.0227 m/s.

Figure C1(a): Pressure response of Case 5 (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 20 cm³/min.
Figure C1(b): Pressure response of Case 5 (0.5 wt% FA-406, 0.38/0.5"ID/OD Nylon6 pipe) at fixed liquid injection rate of 40 cm³/min.

Figure C1(c): Pressure response of Case 5 (0.5 wt% FA-406, 0.38/0.5"ID/OD Nylon6 pipe) at fixed liquid injection rate of 60 cm³/min.
Figure C1(d): Pressure response of Case 5 (0.5 wt% FA-406, 0.38/0.5"ID/OD Nylon6 pipe) at fixed liquid injection rate of 80 cm³/min.

Figure C2(a): Pressure response of Case 6 (5.0 wt% Aquet-944, 0.38/0.5"ID/OD Nylon6 pipe) at fixed liquid injection rate of 20 cm³/min.
Figure C2(b): Pressure response of Case 6 (5.0 wt% Aquet-944, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 40 cm³/min.

Figure C2(c): Pressure response of Case 6 (5.0 wt% Aquet-944, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 60 cm³/min.
Figure C2(d): Pressure response of Case 6 (5.0 wt% Aquet-944, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 80 cm³/min.

Figure C3(a): Pressure response of Case 7 (0.5 wt% Aquet-944, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 20 cm³/min.
Figure C3(b): Pressure response of Case 7 (0.5 wt% Aquet-944, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 40 cm$^3$/min.

Figure C3(c): Pressure response of Case 7 (0.5 wt% Aquet-944, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 60 cm$^3$/min.
Figure C3(d): Pressure response of Case 7 (0.5 wt% Aquet-944, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 80 cm³/min.

Figure C4(a): Pressure response of Case 8 (0.1 wt% Aquet-944, 0.38/0.5”ID/OD Nylon6 pipe) at fixed liquid injection rate of 20 cm³/min.
Figure C4(b): Pressure response of Case 8 (0.1 wt% Aquet-944, 0.38/0.5"ID/OD Nylon6 pipe) at fixed liquid injection rate of 40 cm$^3$/min.

Figure C4(c): Pressure response of Case 8 (0.1 wt% Aquet-944, 0.38/0.5"ID/OD Nylon6 pipe) at fixed liquid injection rate of 60 cm$^3$/min.
Figure C4(d): Pressure response of Case 8 (0.1 wt% Aquet-944, 0.38/0.5” ID/OD Nylon6 pipe) at fixed liquid injection rate of 80 cm³/min.
APPENDIX D

EXPERIMENTS IN INCLINED PIPES: CASE 1 TO CASE 5 IN CHAPTER 5

Appendix D shows pressure data from the experiments at different inclination angles in Chapter 6. Appendix D consists of results from Base Case (horizontal, inclination angle = 0°); Case 1 (upward, 45°); Case 2 (upward, 90°); Case 3 (downward, 45°); and Case 4 (downward, 90°). In all experiments, 0.5 wt% Cedepal FA-406 is applied. Another set of experiments, Case 5, is followed at 45° upward inclination angle in order to see the transition from segregated flow to plug flow pattern. Note that the injection flow rate of 100 cm³/min corresponds to the superficial velocity of 0.0747 ft/s or 0.0227 m/s.

Figure D1(a): Pressure response of Case 1 (Inclination 45° Upward) (Nylon 6 pipe, 0.5” OD, FA-406, 0.5 weight% conc.) at fixed liquid injection rate of 20 cm³/min.
Figure D1(b): Pressure response of Case 1 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 40 cm³/min.

Figure D1(c): Pressure response of Case 1 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 60 cm³/min.
Figure D1(d): Pressure response of Case 1 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 80 cm³/min.

Figure D2(a): Pressure response of Case 2 (Inclination 90° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 20 cm³/min.
Figure D2(b): Pressure response of Case 2 (Inclination 90° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 40 cm³/min.

Figure D2(c): Pressure response of Case 2 (Inclination 90° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 60 cm³/min.
Figure D2(d): Pressure response of Case 2 (Inclination 90° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 80 cm³/min.

Figure D3(a): Pressure response of Case 3 (Inclination 45° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 20 cm³/min.
Figure D3(b): Pressure response of Case 3 (Inclination 45° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 40 cm³/min.

Figure D3(c): Pressure response of Case 3 (Inclination 45° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 60 cm³/min.
Figure D3(d): Pressure response of Case 3 (Inclination 45° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 80 cm³/min.

Figure D4(a): Pressure response of Case 4 (Inclination 90° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 20 cm³/min.
Figure D4(b): Pressure response of Case 4 (Inclination 90° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 40 cm³/min.

Figure D4(c): Pressure response of Case 4 (Inclination 90° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 60 cm³/min.
Figure D4(d): Pressure response of Case 4 (Inclination 90° Downward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 80 cm³/min.

Figure D5(a): Pressure response of Case 5 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 10 cm³/min.
Figure D5(b): Pressure response of Case 5 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 20 cm³/min.

Figure D5(c): Pressure response of Case 5 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 40 cm³/min.
Figure D5(d): Pressure response of Case 5 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 60 cm³/min.

Figure D5(e): Pressure response of Case 5 (Inclination 45° Upward) (0.5 wt% FA-406, 0.38/0.5”ID/OD Nylon 6 pipe) at fixed liquid injection rate of 80 cm³/min.
VITA

Rahul N. Gajbhiye was born in India. He did his schooling in the historic city of Achalpur which is situated in central India. While studying, he was always fascinated with mega machinery and its applications in various field of engineering. This inclination drove him to embark on this long journey of engineering education.

After high-school, he moved away from home to the city of Pune known for its quality education to pursue his bachelor’s degree in petroleum engineering at Maharashtra Institute of Technology. He also holds a master degree in computer application from Amravati University.

In 2002, he joined as a lecturer in petroleum engineering department at Maharashtra Institute of Technology, Pune. As a lecturer, he taught courses in drilling and production engineering at undergraduate level for four years.

During his academic career, he felt the need of higher education to fulfill his aspirations of research. He then joined the Craft & Hawkins Department of Petroleum Engineering at Louisiana State University as a doctoral student in spring 2007.

Though his main interest lies in research he wishes to gain industry exposure to identify gaps in technology which need to be filled via research. His research interest includes drilling and production operations, underbalanced drilling, foam hydraulics and multiphase flow.