Front. Energy 2020, 14(3): 635–643
https://doi.org/10.1007/s11708-018-0582-y

RESEARCH ARTICLE

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Experimental investigation of multiphase flow behavior in drilling annuli using high speed visualization technique

Abstract Imaging with high definition video camera is an important technique to visualize the drilling conditions and to study the physics of complex multiphase flow associated with the hole cleaning process. The main advantage of visualizing multiphase flow in a drilling annulus is that the viewer can easily distinguish fluid phases, flow patterns and thicknesses of cutting beds. In this paper the hole cleaning process which involves the transportation of cuttings through a horizontal annulus was studied. The two-phase (solid-liquid) and the three-phase (solid-liquid-gas) flow conditions involved in this kind of annular transportation were experimentally simulated and images were taken using a high definition camera. Analyzing the captured images, a number of important parameters like velocities of different phases, heights of solid beds and sizes of gas bubbles were determined. Two different techniques based on an image analysis software and MATLAB coding were used for the determinations. The results were compared to validate the image analyzing methodology. The visualization technique developed in this paper has a direct application in investigating the critical conditions required for efficient hole cleaning as well as in optimizing the mud program during both planning and operational phases of drilling. Particularly, it would be useful in predicting the cuttings transport performance, estimating solid bed height, gas bubble size, and mean velocities of bubbles/particles.

Keywords visualization, horizontal annulus, hole cleaning, multiphase flow, image analysis, flow regime

Received Jan. 22, 2018; accepted Apr. 20, 2018; online Sept. 10, 2018

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1 Introduction

The advantages of imaging technology in the drilling industry can come in different possible ways, for instance, distinguishing the fluid type, defining the reasons behind pipe sticking and hole cleaning problems, and visualizing the transport behavior of cuttings [1,2]. It has the potential to play a significant role in studying the physics behind the hole cleaning issues in horizontal well drilling or extended reach drilling [3–5]. The key issue in this kind of drilling process is the unknown mechanism of cutting transportation which can involve complex two- or three-phase flow through an annular passage [3,6,7].

In general, the behavior of a multiphase flow as compared to a single-phase flow in an annulus is much more complicated. The main reason is the density difference of the phases. The viscous impediment along the wall for each phase is not the same because of varying densities. As a result, phase velocities may vary quite significantly [8]. A significant contributor to this kind of complex flow behavior is the gravitational force, which makes the solid fragments to be deposited at the bottom of the annular section during the hole cleaning operation. Failure to remove drill cuttings from the well bore will cause deposition followed by accumulation in the annulus which may result in pipe sticking, eccentric annulus, and/or reduced penetration rate [9]. Previous experimental and numerical studies indicated that the transportation of cuttings was affected by many parameters, such as diameter, rotation speed, well inclination, eccentricity, and drilling fluid rheology [3,6,10–13].

The effects of different drilling parameters on hole cleaning for water based drilling fluids in horizontal and deviated wells were studied quite extensively [11,13–17]. Duan et al. [18] attributed the hole cleaning efficiency to different flow phenomena such as rotational speed of inner drill pipe, shear thinning property of a non-Newtonian drilling fluid, and inertial effects resulting from pipe eccentricity and geometric irregularities (drill pipe wobbling or eccentricity variation). It was also noticed that the mud viscosity would affect the hole cleaning efficiency depending on the rotational speeds of drill pipes. Lower speed exerted on the fluid less shear thinning effects which assisted to deposit solids on the walls. As the rotation speed was increased, this effect diminished by creating a helical pattern around the annulus. Duan et al. [18] also concluded that the drill pipe rotation would not only decrease the cuttings concentration in a horizontal annulus but also result in a considerable reduction in frictional pressure loss. Ozbayoglu and Sorgun [19] observed that the drill pipe rotation enhanced cuttings removal. In an eccentric annulus, for both high and low viscosity fluid, the bed height was considerably decreased with the increase in rotation. The eccentric annuli created an inertial effect which became predominate and reduced the counteracting shear thinning effect [20]. However, Ravi & Hemphill [13] and Ofei [21] presented the effects of drill pipe rotation on pressure drop and solid concentration. Newtonian fluid in eccentric annuli was shown to increase the pressure gradient as rotational speed of the inner-pipe increased. The increase in frictional pressure loss was attributed to inertial effects. In a slightly eccentric annulus, shear-thinning effects dominated the counteracting inertial effects, whereas inertial effects became predominant in a highly eccentric annulus.

2 Background

Compared to the volume of investigations on the effect of various drilling parameters on hole cleaning efficiency, a limited number of works have been conducted on the behavior of flow regimes in a horizontal annulus [2,3,22–25]. The cuttings generated in the well bore during drilling can be transported to the surface by several different mechanisms. The specific mechanism of the transportation follows various flow patterns which depend mainly on well bore angle, drill pipe rotation, and flow rate of drilling fluid [24,26,27]. The high-speed imaging technology enables us to identify the flow regimes by analyzing the captured images. Most prominent multiphase flow regimes are schematically presented in Fig. 1.

The significant gas-liquid flow regimes in a horizontal annulus can be described as the bubbly flow: dispersion of small sized bubbles in the liquid; the plug flow: mixture of liquid and large sized bubbles with some tiny bubbles; the slug flow: mixture of liquid and, usually bullet shaped, large gas slugs; the wavy flow: gas phase flows separately on top of denser liquid phase and forms a wavy interface; and the annular flow: liquid flows as a thin film on the wall of the pipe.

In solid-liquid flows, solid particles moving through the annulus can develop into several patterns [25]. Stationary bed refers to the flow regime when liquid flows over a stationary solid bed formed on the lower wall of an annulus. This kind of phase distribution occurs when the velocity of a liquid is moderate to low. When liquid flow-rate increases, the stationary bed breaks up in a pattern of moving dunes. Scouring regime may develop when the flow-rate is increased further. Some particles roll on the dunes in this flow regime, while the solid accumulates in the lower part of the dunes. This mechanism pushes the solids in the flow direction. Dispersed flow regime occurs because of the high liquid flow-rate in the annular horizontal section. As illustrated in Fig. 1, various patterns like plug, slug, stratified and annular flow regimes can arise in solid-liquid-gas multiphase flow through an annulus [4,23]. In plug flow, the gas bubbles move through the upper part of the annulus and have a negligible effect on the solid flow. Increasing gas flow rate usually increases the plug sizes and, ultimately, develops a slug flow regime. The transportation of solid particles in such multiphase flow is very complicated as the particles flow either as a dispersed phase or make a stationary bed. A gas-liquid interface is produced in the stratified flow with liquid flowing at the bottom of the annulus. In the annular flow, the solid particles can be transported in the liquid film and/or the gas core.

The experimental setup used for the present study was developed by incorporating a high-speed camera in a multiphase annular flow system which could replicate the actual drilling conditions. The setup provided an opportunity to visualize and capture images of different multiphase flow regimes under various flow conditions in the horizontal annulus. Examining the high quality images, the types of flow patterns, the speeds of different phases, the heights of solid bed, and the heights of gas-liquid interfaces could be distinguished. The objective was to develop a convenient and useful image analyzing methodology which would be beneficial to the drilling industry.

3 Experimental setup

The experiments were conducted in the Advanced Multiphase Flow Assurance and Production Laboratory in Texas A&M University at Qatar. The facility consists of a flow loop system with the following major components: pumps, a compressor, control valves, Coriolis flow meters, pressure transducers, an annular test section, a separator, an agitator, a storage tank, a data acquisition system, and a high-speed camera.

The complete setup is presented schematically in Fig. 2.

The flow system consisted of a 6.4 cm × 11.4 cm (2.5 in × 4.5 in) and 616 cm (20 ft) long annulus having an annular flow area of 70.9 cm^2. The annulus was made up of an outer pipe and an inner aluminium pipe. The outer pipe was comprised of five sections, each having a length of 100 cm. The three sections were made of transparent acrylic pipes, and the other two were made of steel. All sections of the outer pipe had an internal diameter of 11.43 cm (4.5 in).

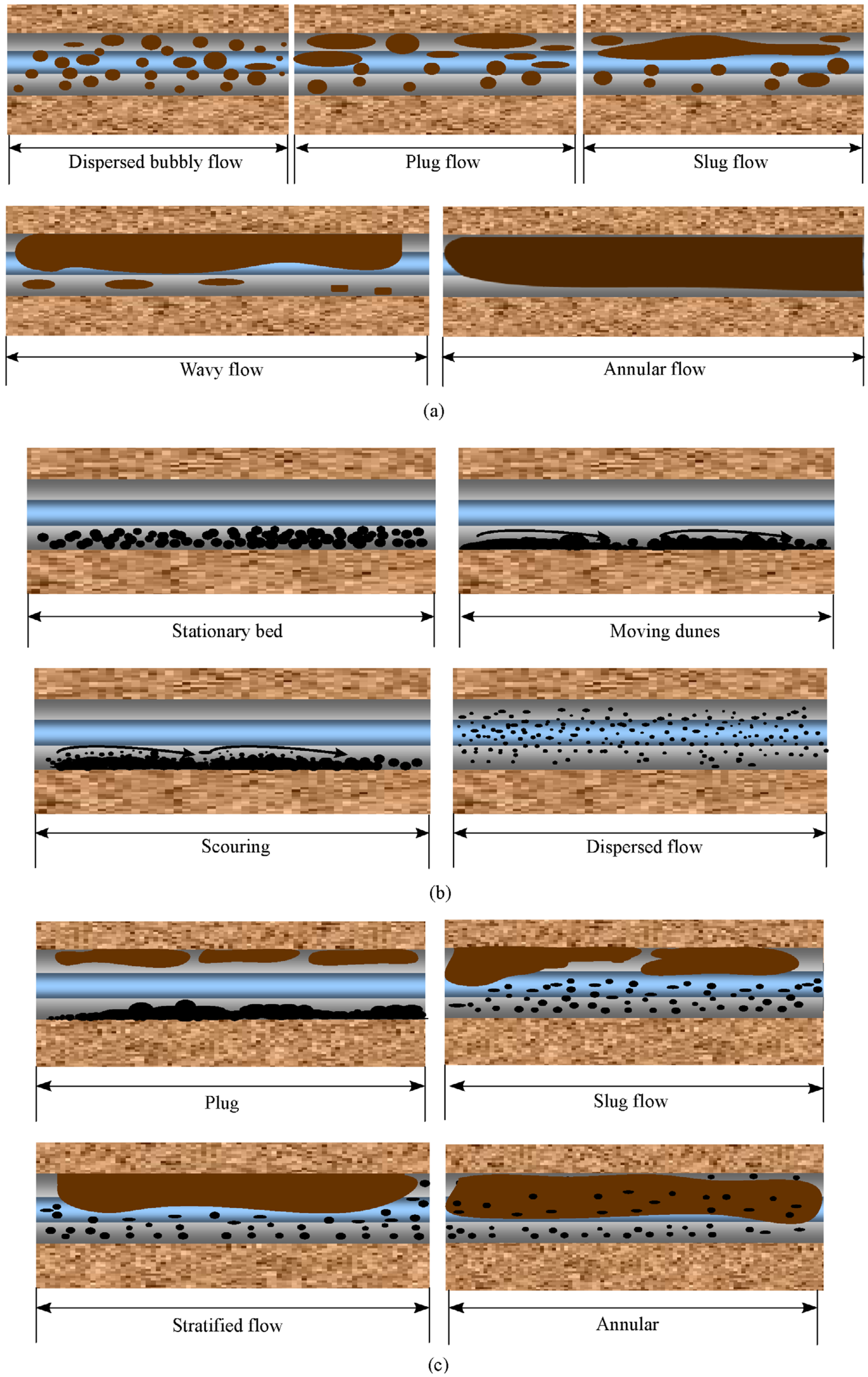
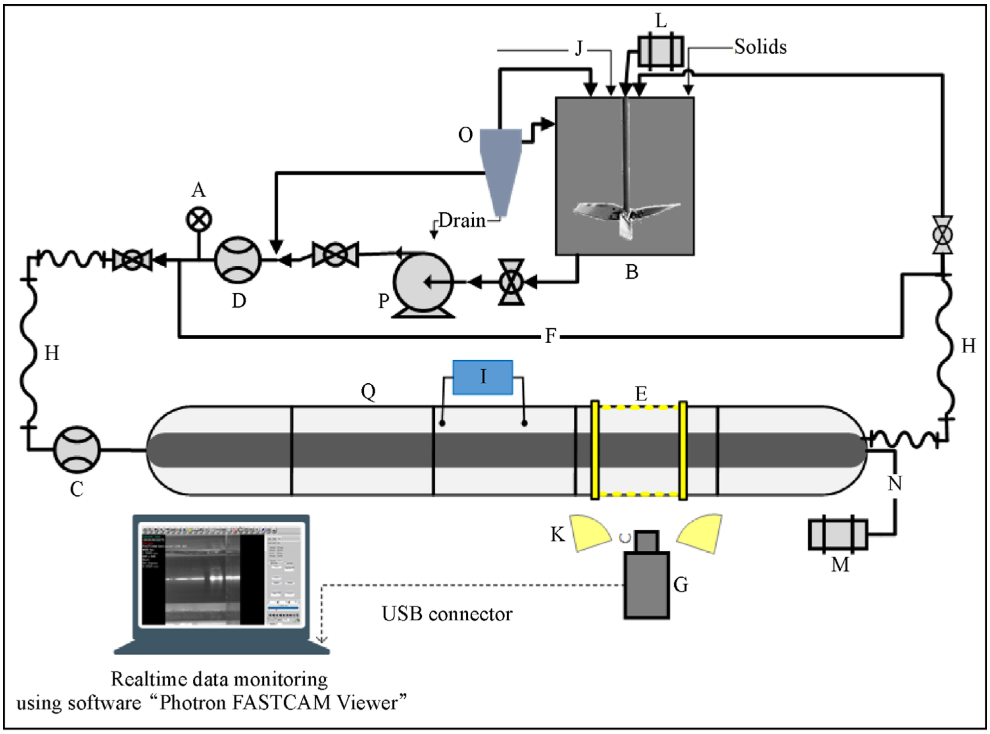


Fig. 1 Schematic presentation of prominent flow regimes of horizontal multiphase flow in an annular pipe
(a) Gas-liquid two-phase flow; (b) solid-liquid two-phase flow; (c) solid-liquid-gas three-phase flow

The inner pipe of the annular flow section also had five pipe sections as of outer pipe with a similar length. The outer diameter of the inner pipe section was 6.35 cm (2.5 in). The inner pipe was attached to a variable-speed motor that enabled its rotation at 0–150 r/min. In addition to rotating, the inner pipe could be placed eccentrically. The whole unit was setup on a frame capable of inclining from the horizontal position to about 15°. The system included a



A—Pressure gauge; B—Tank with agitator; C—Coriolis air flow meter; D—Coriolis liquid flow meter; E—Refractive box for visualization; F—Rigid pipe; G—CCD camera; H—Flex hose; I—Absolute differential pressure; J—Water supply; K—Light projectors; L—Agitator motor; M—Motor for rotating the inner tubes; N—Inner tube rotating mechanism; O—Cyclone for solids separation; P—Centrifugal pump; Q—2.5 in by 4.5 in annulus with Acrylic outer shell and aluminum inner pipe

Fig. 2 Schematic presentation of experimental setup

flow tank with a capacity of 10^6 mL (265 gals) equipped with an agitator. The system could be operated with a maximum pressure of 1 bar (15 psig) with air-water (two-phase) and 2 bar (30 psig) with only water (single-phase) flowing in the annulus. The range of operating pressure for the current experiments was 0.10–0.55 bar (1–8 psig).

A centrifugal slurry pump was used with a maximum flow rate of 21.3 L/s, giving a maximum velocity of 3 m/s in the annulus. A digital pressure sensor was placed near the outlet of the pump (Toshiba) to have a controlled circulation of liquid through the loop. One liquid Coriolis flow meter, one air Coriolis flow meter, one multivariate pressure transducer (MVT), and two digital pressure sensors were installed in the system to control and measure the flow. The Coriolis flow meter and MVT were made by Emerson Micromotion Technologies and Rosemount, respectively. Two pairs of pressure taps were installed with a proper distance from the inlet and outlet to the annulus so that the data could be acquired from the fully developed flow section. These taps were connected to differential pressure transducers to measure the differential pressure. Solid particles were injected into the tank after achieving a stable liquid flow-rate. Once the flow of particle-water mixture became steady, the data acquisition system was activated. Solid glass beads made up of soda lime were used for the experiments. The diameter and density of the solid particles were 2–3 mm and 2500 kg/m^3, respectively.

A CCD camera, Photron FASTCAM SA-X2 was used for recording images. It is a high-performance camera system which uses the latest imaging technology to meet the requirements of the most demanding high-speed imaging applications. NIKON G type lenses were compatible with the objective lens mount of the camera. The distinguishing feature of this camera was that the images could be visualized in a very slow motion. The range of image recording speed was 1000 – 120000 frames per second (fps). A Photron FASTCAM software was available to operate the camera remotely from a computer. The software could also be used to analyze the recorded images.

A refractive index matching (RIM) box was fitted on the annular test section (E in Fig. 2). It was a rectangular Plexiglas box. The purpose of using the RIM box was to minimize the effect of pipe curvature [28,29]. The void area between the rectangular box and the outer pipe was filled with water. Two projection lights were placed in front of the box. Projection lights were carefully adjusted to assure the exact identification of the gas-liquid or solid-liquid interface(s).

4 Results and discussion

Experiments were performed to investigate the phenomena of multiphase flow through a drilling annulus with the application of high-speed imaging technology. Major controlled variables were fluid flow rate and input solid concentration. The experimental conditions along with the results of flow regime are summarized in Table 1. It should be mentioned that the inner pipe of the annulus was concentric and stationary for all experiments. Examples of images captured under different flow conditions are presented in Fig. 3. Notice that in Fig. 3(a), the area between the inner and the outer pipe was occupied by water and by producing a single-phase flow. However, in Fig. 3(b), three-quarters of the annulus was covered by glass beads, thus, by making a phenomenon of solid-liquid two-phase flow. Besides, in Fig. 3(c) the annulus was flowing with water and gas bubbles. Hence, the transition of this phase is termed as gas-liquid two-phase flow.

The results of the air-water two-phase flow experiments are demonstrated in Fig. 4. In Figs. 4(a) and 4(b), the annulus was flowing with water and air. However, the air bubbles were separated with the water and flowing on the top of the annulus. But, in Fig. 4(c), there was a complete separation between air and water. As water and air was making a clear interface between the inner wall of the annulus. In addition, Fig. 4(a) shows the bubbly flow. This flow regime was obtained when the mass flow rate of water (m_w) was 270 kg/min and the volumetric flow rate of air (Q_a) was 6.5 l/h. The corresponding system pressure (P_s) was 4.35 psi (0.3 bar). As the flow rates of water and air were increased to 340 kg/min and 7.02 l/h, respectively, the P_s changed to 5.8 psi (0.4 bar). However, the increased pressure did not produce any significant transformation of the flow regime. The bubbly flow was continuing, although the bubbles started to adhere to one another and stopped flowing as dispersedly as before. Finally, the flow rates of water and air were reduced to 163 kg/min and 5.22 l/h, respectively. The corresponding P_s was 2.9 psi (0.2 bar). Due to reducing flow rates, a stratified flow regime turned up with a clear wavy interface on the upper part of the annulus. Similar transformation of flow regimes in both annulus and pipe was observed by other investigators [2,6,9,12,29].

Table 1 Summary of experimental flow conditions and results (annulus orientation: concentric, solid particle size: 2–3 mm, temperature: 25°C)

Phase components	Water flow rate $m_w/(\text{kg}\cdot\text{min}^{-1})$	Air flow rate $Q_a/(\text{l}\cdot\text{h}^{-1})$	System pressure P_s/bar	Input solid C_s/%	Flow regime	$\frac{m_{gas}}{m_{Total}}$/%
Water	160.8	–	0.1	–	–	–
Water and air	269.6	6.2	0.3	–	Bubbly	0.039
Water and air	339.8	7.0	0.4	–	Bubbly	0.035
Water and air	163.2	5.2	0.2	–	Wavy	0.054
Glass bead and water	267.8	–	0.3	1.2	Stationary bed	–
Glass bead, water, and air	268.5	6.47	0.29	1.8	Bubbly flow with stationary bed	0.040
Glass bead, water, and air	163.19	5.31	0.10	1.8	Stratified flow with stationary bed	0.055

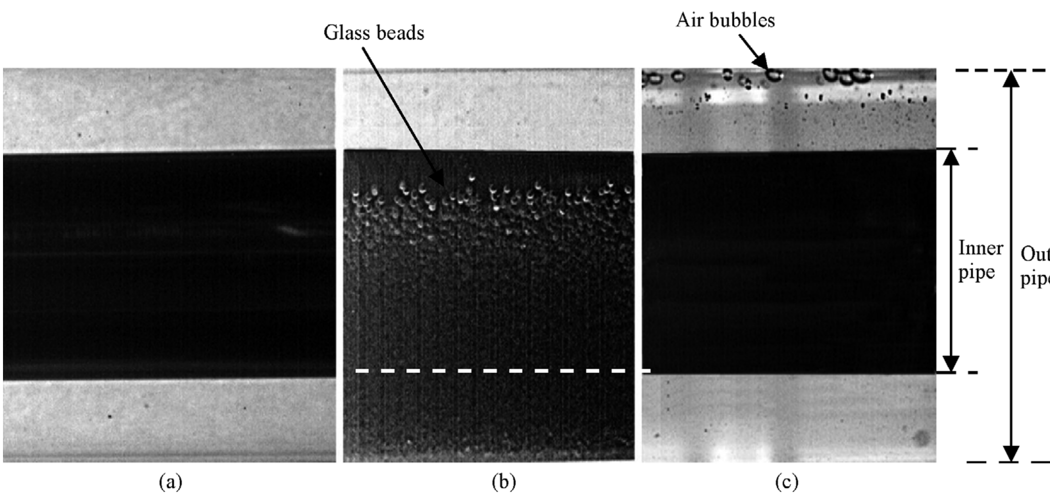


Fig. 3 Images illustrating different multiphase flow systems
(a) Single phase flow of water (water flow rate, m_w: 160.8 kg/min); (b) two phase flow of glass beads and water (solid input fraction, C_s: 1.2%; water flow rate, m_w: 267.8 kg/min); (c) two phase flow of air and water (air flow rate, Q_a: 6.2 l/h; water flow rate, m_w: 269.6 kg/min; m_{gas}/m_{Total}: 0.039%)

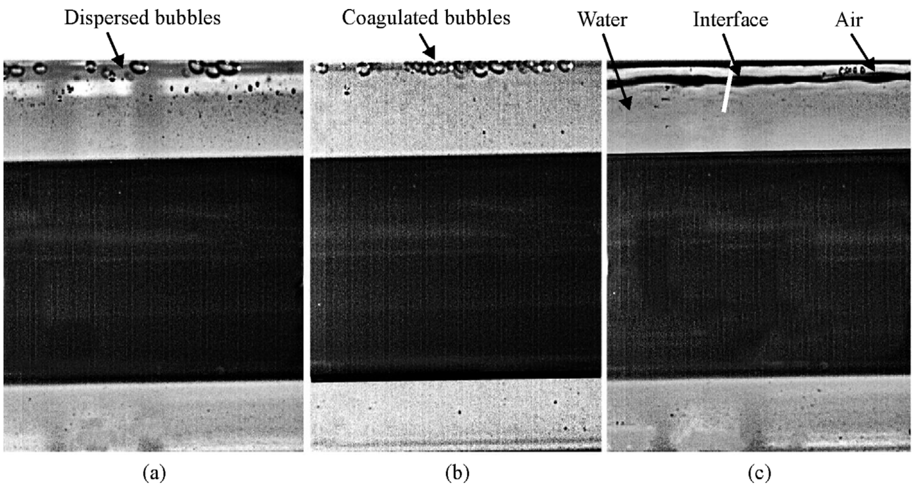


Fig. 4 Presentation of air-water two phase flow experiments
(a) Dispersed bubbles (air flow rate, Q_a: 6.2 l/h; water flow rate, m_w: 269.6 kg/min; m_{gas}/m_{Total}: 0.039%); (b) coagulated bubbles (air flow rate, Q_a: 7 l/h; water flow rate, m_w: 339.8 kg/min; m_{gas}/m_{Total}: 0.035%); (c) wavy interface (air flow rate, Q_a: 5.2 l/h; water flow rate, m_w: 163.2 kg/min; m_{gas}/m_{Total}: 0.054%)

The test conditions of glass beads-water two-phase and glass beads-water-air three-phase flows are presented in Table 1. Figure 5(a) was a solid-liquid two-phase flow, where the annulus was flowing with water and three-quarters of the annulus was flowing with solid, whereas, Figs. 5(b) and 5(c) were three-phase flow of solid-liquid-gas flowing with solid as glass beads, liquid as water and gas as air. The stationary bed flow regime of the solid-liquid flow is illustrated in Fig. 5(a). It was obtained when m_w was 267 kg/min while the input concentration of solid (C_s) was 1.2% (6 kg glass beads in 500 kg water). The corresponding P_s was 4.20 psi (0.29 bar). It was observed from the recorded video that the glass beads at the interface was moving slowly. That is, a stationary bed with saltation was obtained under the tested flow condition. Next, air was introduced in the annulus at 6.47 L/h and the C_s was increased to 1.8% (9 kg glass beads in 500 kg water) while m_w remained the same as before. Under the changed flow condition, P_s was 4.20 psi (0.29 bar). A combination of bubbly flow and stationary bed was observed for this three-phase flow test. Figure 5(b) shows the flow regime. Both dispersed and coagulated bubbles were visible in the upper section of the annulus. On the lower part, the glass beads continued moving as a stationary bed with saltation. Finally, the flow rates of water and air were reduced to 163.20 kg/min and 5.3 L/h, respectively. P_s reduced to 1.45 psi (0.1 bar). Due to reducing flow rates, the bubbly flow regime of air turned into a stratified flow regime with a clearly visible wavy interface. However, the glass beads were still flowing as a staionary bed with saltation.

The images captured during the experiments were further used to estimate the height of the solid bed, and

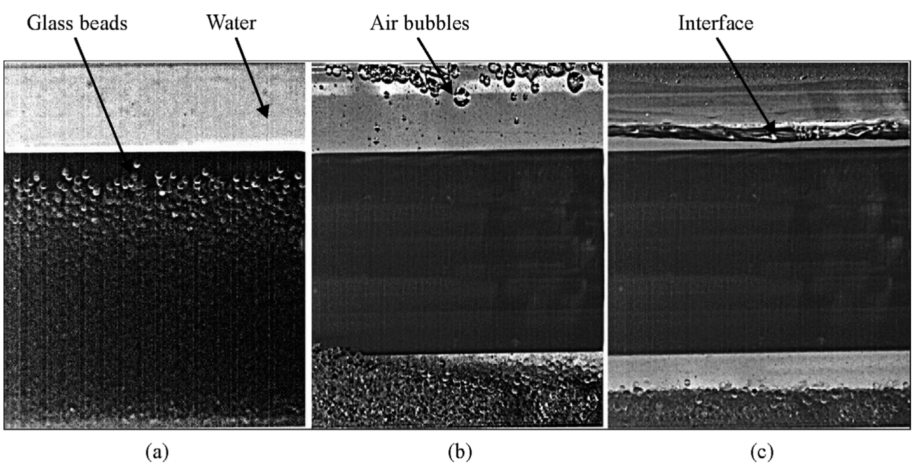


Fig. 5 Presentation of flow regimes in two phase (glass beads-water) and three-phase (glass beads-water-air) flow experiments
(a) Stationary bed (m_w = 267.8 kg/min, C_s = 1.2%); (b) bubbly flow with stationary bed (m_w = 268.5 kg/min, Q_a = 6.47 l/h, C_s = 1.8%; m_{gas}/m_{Total}: 0.040%); (c) stratified flow with stationary bed (m_w = 163.19 kg/min, Q_a = 5.31 l/h, C_s = 1.8%; m_{gas}/m_{Total}: 0.055%)

the size and speed of the bubble/particle. Two separate image analyzing software, Photron FASTCAM and MATLAB were used for the estimation. For the calculations of velocities, a bubble or a solid particle was selected randomly whose displacement was analyzed using the software [12]. The size of bubble/solid particle was calculated by averaging the estimated sizes of approximately 22 bubbles/particles present in an image.

Image analysis with Photron FASTCAM required calibrating the image. For this purpose, the image was uploaded in the software and the 'scale calibration window' was opened. The tab, 'calibrate of distance between two points' was selected in the window. As the ID of the outer shell (4.5 in) and the OD of the inner pipe (2.5 in) were known, the images were calibrated based on either or both of these distances. After completing the calibration, it was possible to estimate different bed heights, bubble/particle sizes and bubble/particle velocities using the software. The velocities were calculated based on the assumption that velocity is the rate of displacement. The displacement of a bubble/particle and the time required for the displacement could be known by analyzing the images using the Photron FASTCAM software. The results of the estimated values of different parameters are presented in Table 2.

After analyzing the images using Photron FASTCAM, MATLAB was used for the same purpose. The MATLAB developed by Math Works (www.mathworks.com) is a high-level proprietary programming language which is equipped with an interactive computing environment. It is usually used for numerical computation and programming. It has also been used successfully to analyze images [5,6]. The MATLAB coding, imtool was used in the present study. An image was divided into pixels with the coding and a pixel size was calibrated with respect to a known length, such as, the diameter of the inner pipe. After calibrating, different heights and sizes in the image could be calculated from the associated number of pixels. The values of the parameters estimated using MATLAB are listed in Table 3.

It is clearly observed from Tables 2 and 3 that there is a good agreement between the values of different parameters determined by using the Photron FASTCAM software and MATLAB coding. The overall difference was less than 20%. That is, the values obtained on the basis of two independent methods agree within an acceptable limit. This agreement supports the software based approach of image analysis which is a very simple and straight forward methodology. It does not require any special knowledge.

5 Summary

The objective of the present paper was to provide detailed information about the application of high-speed imaging technology in analyzing the multiphase flow in a drilling annulus. The reported results can be summarized as follows:

1) The solid-liquid, gas-liquid, and solid-gas-liquid multiphase flow experiments were conducted in a 4.5 in by 2.5 in drilling annulus (diameter ratio: 0.56). The flow rates of liquid (water) and gas (air) were varied within a range of 160–340 kg/min and 5.2–7 L/h, respectively. The input solid (2–3 mm glass beads) concentration was 1.2%–1.8% (wt) and the range of system pressure was 1.45–7.25 psi (0.1–0.5 bar).

Table 2 Values of different parameters calculated using Photron FASTCAM

Figure #	Bubble size /mm	Thickness of water layer /mm	Height of water-air interface/mm	Thickness of solid bed/mm	Mean velocity of solid particles/($m \cdot s^{-1}$)	Mean velocity of gas bubbles/($m \cdot s^{-1}$)
4(a)	5.5	–	–	–	–	0.5
4(b)	5.8	–	–	–	–	0.2
4(c)	–	108.2	5.9	–	–	–
5(a)	–	–	–	73.62	1.5	–
5(b)	5.8	–	–	23.03	–	–
5(c)	–	93.6	20.6	12.24	0.7	–

Table 3 Values of different parameters calculated using MATLAB

Figure #	Bubble size/mm	Thickness of water layer/mm	Height of water-air interface/mm	Thickness of solid bed/mm
4(a)	4.60	–	–	–
4(b)	5.10	–	–	–
4(c)	–	106.20	4.60	–
5(a)	–	–	–	76.56
5(b)	5.90	–	–	23.40
5(c)	–	93.71	20.41	12.25

2) The flow regimes observed under the tested flow conditions were stationary solid bed with saltation (solid-liquid flow), bubbly flow with both coagulated and dispersed bubbles (gas-liquid flow), stratified flow (gas-liquid flow), and combinations of stationary bed-bubbly flow and stationary bed-stratified flow (solid-gas-liquid flow).

3) Two separate methodologies based on a commercial software (Photron FASTCAM) and a MATLAB coding (imtool) were used to analyze the high quality images. The analysis consisted of the estimation of different parameters, such as the height of solid bed and thickness of water/air layer. The image analysis technique can be used to conduct research on the hole cleaning issues of the drilling industry.

Acknowledgements The authors are grateful to the Qatar Foundation, Texas A&M University at Qatar, and Qatar University. The authors would also like to acknowledge the start-up fund provided by Texas A&M University, Qatar.

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