Study of Two-Phase Flow by Laser Image Processing

A new, unobtrusive method for liquid-liquid two-phase flow data collection was proved to be reliable in this research. Drop size distributions and concentration profiles were determined for a dilute water-in-kerosene system under horizontal straight pipe flow using this technique, and the Segev model for predicting concentration profiles was tested with the data collected here.

The drop size distributions were found to follow a Rosin-Rammler function for a limited droplet diameter range, and the average value of the exponent in the Rosin-Rammler equation was determined to be 2.0. The velocity where the flow regime makes a transition from stratified to adequately dispersed flow was found to be between 2.0 and 2.2 m/s. Concentration profiles predicted by the Segev model were in general agreement with the profiles determined in this work, and using the proper choice of model parameters noticeably improves the model predictions.

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Introduction

The overall goal of this research program is to increase understanding of the relative importance of parameters affecting turbulent mixing in two-phase pipeline flow. The subsidiary goals of this project are:

1. To prove the reliability of a new, unobtrusive method for turbulent two-phase flow data acquisition;
2. To use this new method to collect data on liquid-liquid two-phase pipeline flow;
3. To validate a theoretical model for such systems

This new method of data acquisition has direct and immediate relevance to a significant problem in the petroleum industry today: the sampling and analysis of the water content in crude oils.

The calculated volumes upon which oil is purchased and sold are often based on the assumption that small samples are representative of the bulk volume; however, obtaining representative petroleum samples is one of the most difficult tasks of the petroleum industry. The assumption of a representative sample depends on knowledge of whether water is dispersed in the hydrocarbon at any given velocity and in any given piping configuration. Unfortunately, the conditions required for adequate dispersion at a sampling site have never been conclusively established. A 0.2% underestimate of water can mean tens of thousands of dollars in overpayments for a typical marine vessel (Hanzevack et al., 1980; Berto, 1982).

The sediment and water found in crude oils tend to settle in stationary tanks because of their greater densities. This density difference also causes water in hydrocarbons to preferentially flow near the bottom of pipes at low velocities. As the velocity is increased, turbulent mixing breaks the water into small droplets that then disperse to different elevations in the pipe. At sufficiently high velocities, the water concentration at any elevation in the pipe is essentially constant, and the flow regime is considered to be adequately dispersed. These water concentration profiles are the primary results of interest in this research. The specific objective of this project is to determine the effect on the water concentration profile caused by the upstream mixing in straight pipe flow as a function of velocity, and to establish the range of velocities where stratified flow makes a transition into adequately dispersed flow.

In meeting this objective, a pulsed laser was used to effectively freeze droplet visual motion as a computer-driven camera captured images containing the droplet information (Hanzevack, 1986). From these data, concentration profiles and drop size distributions were determined and were used in establishing the transition velocity. A relatively new model that predicts con-

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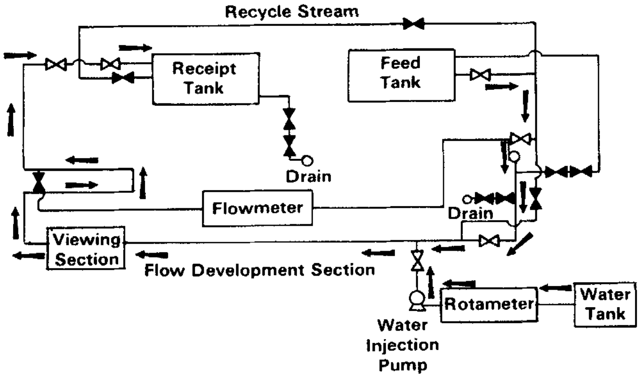

Figure 1. Fluid flow apparatus.

centration profiles was tested for the system used in this research, and then model parameters were adjusted using values experimentally determined in this work.

Experimental Method

A fluid flow rig designed for this research is capable of simulating various field conditions (Powers, 1986). Figure 1 shows a diagram of this flow system. Two 3,785 L carbon steel tanks are used to feed and receive bulk kerosene flow. Kerosene was chosen as the continuous phase primarily because of its transparency. These tanks allow for several minutes of flow at the relatively high velocities used in this research. Kerosene is pumped through a 7.62 cm ID PVC pipeline with flows up to 2.4 m/s.

An optically flat acrylic viewing cell is included in the pipeline for easy data acquisition. Acrylic was chosen for the viewing cell because its refractive index is close to that of kerosene. Water is injected into the center of the pipeline in the direction of kerosene flow through a 6.35 mm opening after the mainline pump and 80 pipe diameters upstream of the viewing cell.

Figure 2 shows the arrangement of the optics and camera used to capture data in this research. Light from a pulsed dye laser is spread by a cylinder lens and is then directed by mirrors through the viewing cell. Five horizontal planes in the pipe are studied.

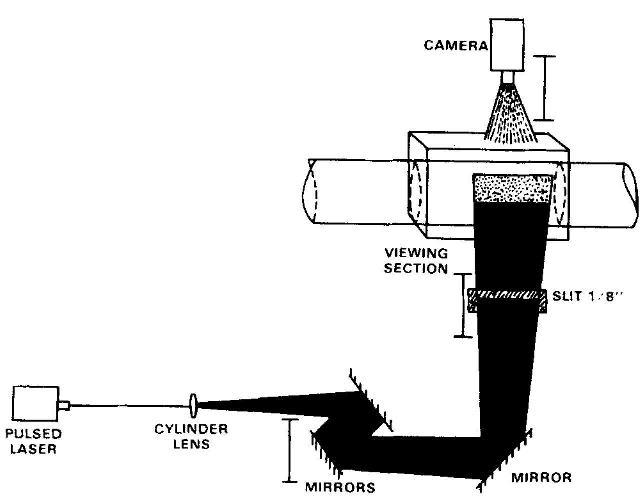

Figure 2. Laser/camera synchronization.

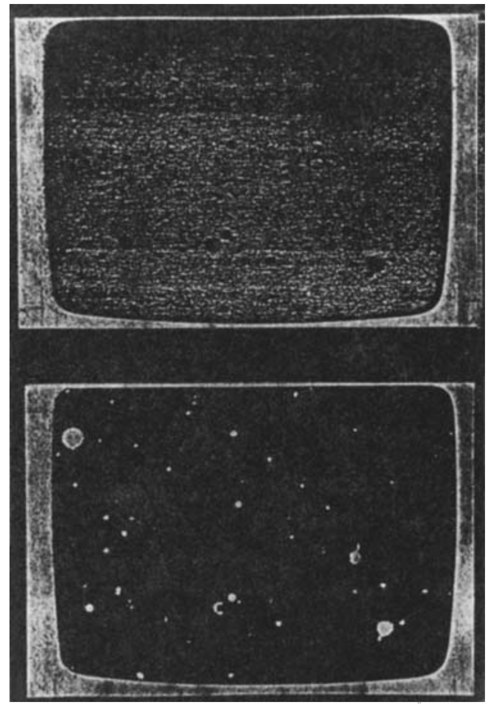

Figure 3. Original and binary images.

The camera is positioned orthogonal to both the hydrocarbon flow and the laser beam. The camera and laser are both controlled by an image-processing computer. Software instructs the laser to trigger at the moment the camera begins to produce a frame. This frame recording the illuminated droplets is stored and then analyzed with available software. Figure 3 shows a typical original picture and the result of processing by thresholding software.

Droplet volumes are added and the total concentration for the image is determined. All drops with comparable diameters are grouped together for drop size distribution summaries. Concen-

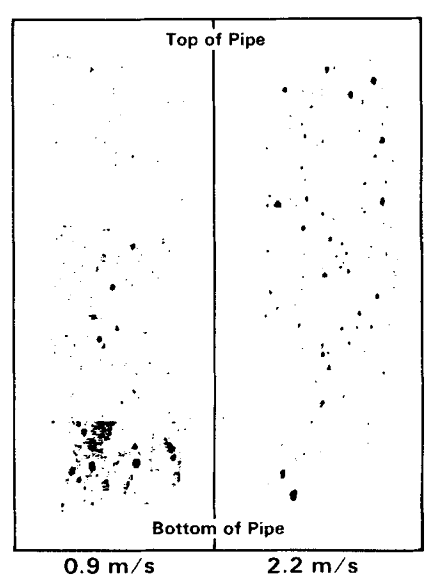

Figure 4. Typical binary image series at 0.9 and 2.2 m/s.

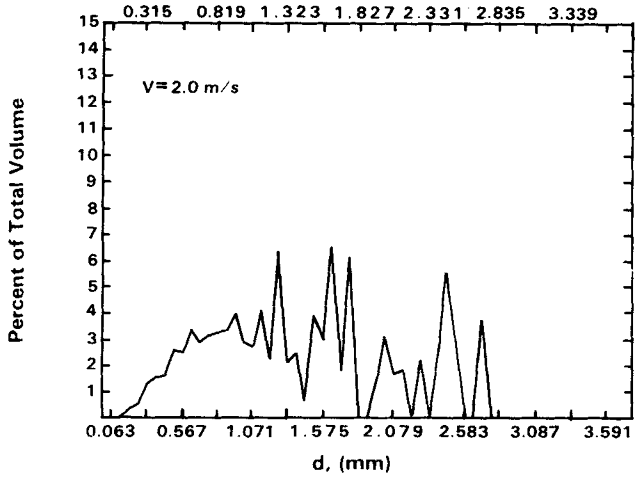

Figure 5. Drop size distribution for 2.0 m/s.

tration profile curves are generated for each velocity studied, and a mass balance is performed to try to account for all of the water introduced into the system. To illustrate this procedure, Figure 4 shows two series of typical concentration profile images across a pipe diameter, at low and high velocity.

Results

Concentration profiles resulting from straight pipe mixing were initially studied for two reasons. First, the reliability of the new, unobtrusive method using computer-based digital image processing had to be proved. Proof of reliability includes generating reasonable profiles while accounting for all water injected into the system. Second, there are still insufficient data on straight pipe flow to adequately define the conditions required to insure dispersed flow.

Experimental evidence shows that the bulk velocity has the greatest effect on concentration profiles and drop size in pipe flow. It is understood that other system parameters affect water dispersion to varying degrees, but because of the large influence of velocity, this research initially concentrated on dispersion as a function of velocity only, holding all other parameters constant.

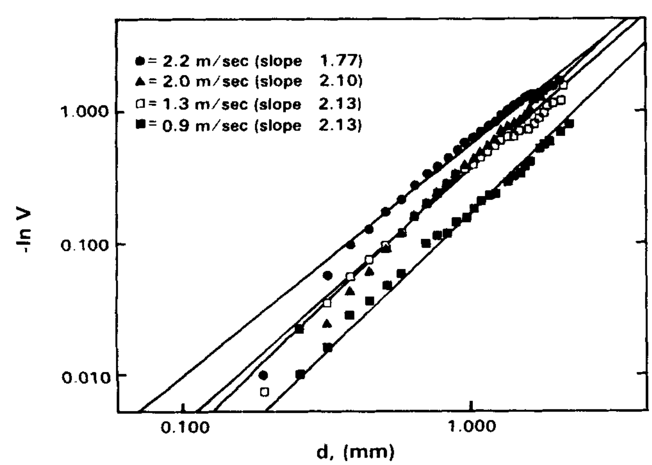

Figure 6. Drop size distribution for 2.2, 2.0, 1.3, and 0.9 m/s as a Rosin-Rammler function.

Table 1. Maximum Drop Sizes

Velocity m/s	n	d_{95} mm	Exp. d_{max} mm	$(n - n)/n$ %
2.2	1.77	2.59	2.77	10.8
2.0	2.10	2.68	2.70	5.6
1.3	1.94	2.98	2.83	2.3
0.9	2.13	3.86	3.15	7.3

Drop size results

Drop size distribution summaries were produced from the data collected at velocities of 0.9, 1.3, 2.0, and 2.2 m/s. Figure 5 shows a typical drop size distribution as drop size vs. occupied percent of total volume. Based on these data, Figure 6, plotted in logarithmic coordinates, shows linearity using a Rosin-Rammler type function. In the Rosin-Rammler equation,

$$V = \exp\left(-(d/d_o)^n\right)$$

where V is the cumulative volume fraction of particles with diameter greater than d. The exponent n can be calculated from the slope of the lines in Figure 6. The parameter d_0 is an arbitrarily chosen normalizing droplet diameter. This equation provides a very satisfactory representation of the data collected in the range of $V = 0.05$ to 0.95. Some interesting observations can be made, based on the results shown in Table 1. The diameter d_{95} is in good agreement with the experimentally determined diameter d_{max}. Furthermore, the values of d_{95} and d_{max} decrease with increasing velocity, as would be expected. The slope n is fairly constant and the average equals 2.0 with error term less than 0.1

Concentration results

Figure 7 shows the profiles generated in this research for water in kerosene at velocities of 0.9, 1.3, 2.0, and 2.2 m/s. Relative concentration or water fraction is defined as the experimentally determined water concentration divided by the original water concentration injected. The flow regime is obviously stratified at the lower velocities of 0.9 and 1.3 m/s, while the profiles flatten at the higher velocities. These curves are in general

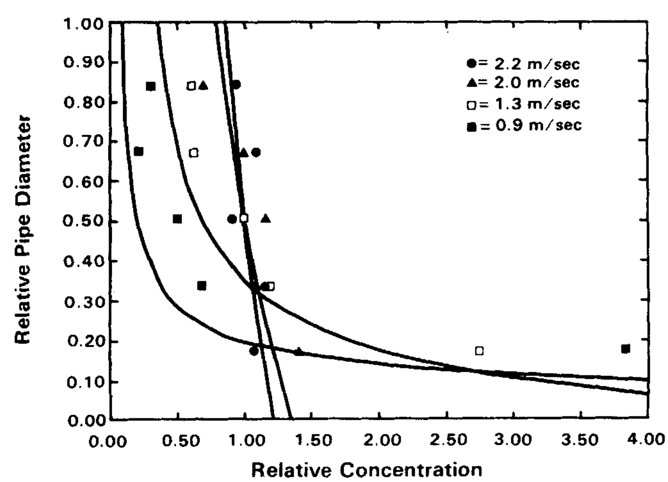

Figure 7. Experimentally determined water concentration profiles.

Table 2. Mass Balances

Velocity m/s	Water Observed/Injected vol. %
0.9	0.90
1.3	1.18
2.0	1.05
2.2	1.02

agreement with the predictions generated by the model of Segev (1984). More in-depth comparisons will be made to this model in the Analysis section.

A mass balance across the pipe area was performed at each velocity, and the results are given in Table 2. Excellent results are obtained for the 2.0 and 2.2 m/s velocities. The water mass balances at the lower velocities do not completely account for the original quantity of water injected, presumably because of the limited number of data taken at these velocities, resulting in a relatively less accurate curve fit.

Many images at any one position at a given velocity are required to yield a true average fraction in this work. The system's turbulence causes the water concentrations to fluctuate widely for different images under the same experimental conditions. Because determination of the transition velocity was the main objective of this stage of our research, few data were captured at 0.9 and 1.3 m/s. The flow was obviously in the stratified regime at these velocities, so efforts were better spent studying the higher velocities. The data captured at 2.0 and 2.2 m/s are more complete than at the lower velocities, but even more data at these higher velocities would further smooth the results.

Analysis

The velocity at which stratified flow makes a transition to adequately dispersed flow in this system is about 2.1 m/s. A more accurate transition velocity could have been isolated if more data were collected, but this was not justified. There is a greater need for the study of other, more interesting piping configurations, and the transition velocity for adequately dispersed flow is already sufficiently bracketed for practical purposes.

Several statistical tests (Miller and Freund, 1977) have been performed to support the assertion that the transition velocity lies between 2.0 and 2.2 m/s. The tests support the belief that the transition velocity is in this range. No test performed rejected hypotheses stating that 2.2 m/s is sufficient velocity to produce adequately dispersed flow.

To be flowing in the adequately dispersed regime, the water fraction should not deviate below 0.95 at the top of the pipe or above 1.05 at the bottom of the pipe, corresponding approximately to an "A" rated sampling location in API/ASTM standards (ASTM Standard D4177, 1982). The difference between the fraction at the top of the pipe and that at the bottom of the pipe should not be greater than 0.1. Testing the hypothesis that the difference in the water fractions between the top and the bottom of the pipe is no greater than 0.1, we find that at 2.0 m/s we can reject this hypothesis for the alternative hypothesis that the difference is greater than 0.1. We cannot reject this hypothesis for data at 2.2 m/s. Testing a second hypothesis, that at the top of the pipe at 2.0 m/s the water fraction is 0.95, we find that we can reject this hypothesis for the alternative hypothesis that

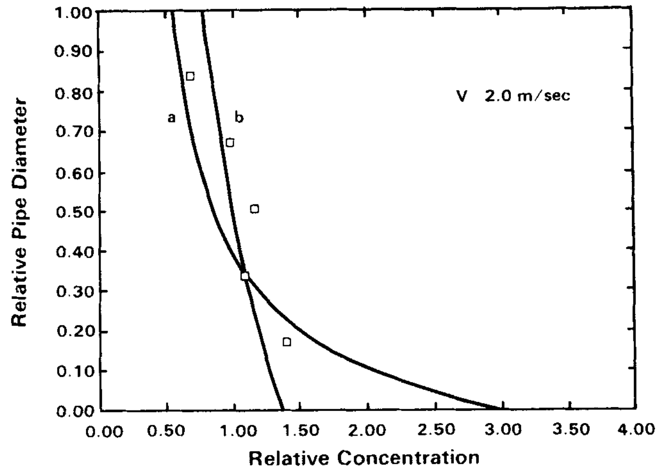

Figure 8. Comparison between Segev model and experimental data for 2.0 m/s.

a. Using Segev parameters, $\xi = 0.255$; $n = 1.5$

b. Using new parameters, $\xi = 1.00$; $n = 2.0$

the water fraction is less than 0.95. We cannot reject this hypothesis at 2.2 m/s.

A second set of tests, using the Kruskal-Wallis H-test method, was performed based on the assumption that all images taken at each position come from the same population, meaning that any analyzed image from a position at the top of the pipe could have just as readily come from a position at the bottom of the pipe. Flows that are adequately dispersed should have this property. This hypothesis can be rejected at 2.0 m/s but not at 2.2 m/s.

These sets of tests cannot prove that the transition velocity is at least 2.2 m/s, but they do indicate that 2.0 m/s is too low for the transition velocity and that 2.2 m/s cannot be rejected as the transition velocity. These tests, as well as the concentration profile's general appearance, support our belief that the transition velocity lies between 2.0 and 2.2 m/s, where 2.1 m/s is a good approximation to the actual velocity.

Figure 8 shows typical data collected in this research, at 2.0 m/s along with the Segev (1984) predictions for this system using his parameter values. Figure 8 also shows predictions for this system using parameters determined in this work concerning the drop size distributions and the eddy diffusivities, where the Rosin-Rammler exponent n is taken to be 2.0. Figure 7 shows the data for all four velocities, and Segev model predictions, using our new parameters. It is clear that the Segev model can predict the correct profile if the paper values of the parameters are used. Future work will attempt to better understand and quantify these parameters.

Conclusions

A new, unobtrusive method for two-phase flow data collection was proven reliable in this research to date. This method can easily be applied to other two-phase flow problems and is recommended because of its objective, rapid, robust, and unobtrusive qualities in data collection and analysis.

On the other hand, the effectiveness of the software depends on the threshold selection. Too high a threshold results in lower predicted concentrations and somewhat different drop size distributions. Too low a threshold causes higher predicted concentrations and more noise in the binary image. Although good results have been obtained using the present method of threshold selection, a more reliable and general automatic threshold selection method is being developed. It will lead to improved modeling capabilities and better parameter estimation.

Drop size distributions for each of the four velocities studied exhibit Rosin-Rammler type distributions over most of the drop diameter range. This has been found to be the case in many other drop size studies as well. The slopes of the curves generated by the Rosin-Rammler type plots do not appear to be affected by velocity.

The transition velocity between stratified and dispersed flow for straight horizontal pipe has been estimated at 2.1 m/s. The Segev model does predict our experimentally determined concentration profiles if proper parameter values are chosen.

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Notation

a = coefficient in least-squares curve
b = coefficient in least-squares curve
d = droplet diameter
d_0 = arbitrary droplet diameter in Rosin-Rammler function
n = exponent in Rosin-Rammler function
V = cumulative volume fraction of particles with diameter greater than d
x = relative pipe diameter at horizontal plane of interest
y = relative concentration
ξ = dimensionless eddy diffusivity

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