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EFFECT OF VELOCITY AND PIPELINE CONFIGURATION ON DISPERSION IN TURBULENT HYDROCARBON–WATER FLOW USING LASER IMAGE PROCESSING

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Abstract—Drop size distribution and concentration profile data for hydrocarbon–water mixtures are obtained in a 8.2 cm dia pipe at a range of velocities for a straight horizontal pipe, horizontal and vertical flow after one bend and vertical flow after three bends. The laser image processing technique employed in this project is proven reliable.

The maximum drop size (d_{99}), is more dependent on the number of upstream interactive bends than on the velocity. The drop size distributions follow a Rosin–Rammler power law. The values of Rosin–Rammler exponents, based on this work, are on average 2.1 for all the configurations studied.

The concentration profiles as a function of velocity for straight horizontal flow are obtained and show the transition from stratified to adequately dispersed flow at about 2.3 m/s velocity. The concentration profiles for horizontal or vertical flow after one bend show dispersed flow in some cases; however, in other cases swirling makes representative sampling more difficult.

Vertical downflow after three interactive bends breaks the droplets to a finer size, and concentration profiles obtained in this location are more uniform than the other configurations studied. Representative sampling can be accomplished in this location even at 0.7–1.0 m/s velocity, in a 8.2 cm pipe.

Key Words: dispersion, mixing, sampling, image processing

INTRODUCTION

The overall goal of this research is to increase understanding of the effects of pipeline configurations on two-phase turbulent liquid–liquid flow. Subsidiary goals of this experimental research are: (1) to assure reliability of a computer-based, digital image processing technique for data acquisition; (2) to create concentration profiles of the dispersed phase as a function of velocity and pipeline configurations; (3) to collect sufficient data that will serve for future theoretical modeling of liquid–liquid two-phase flows; and (4) to assist industry to find the best location for representative sampling for water analysis in water–oil systems.

The fluctuating demand and price of imported crude oil in the 1970s and 1980s have motivated studies of water that naturally occurs in unrefined stock. All extracted crude oil contains a small amount of water, some of which is unmeasured because measuring techniques that have been proposed and implemented so far have one or two major drawbacks. The most common research methods employ conventional photography but this approach is subjective, due to human error. Industrial methods employ probing devices which disturb the flow, making them obtrusive by nature. Accurate water content measurement in oil pipeline flows can only be achieved when the small samples obtained for analysis are representative of the bulk volume. Obtaining representative samples is one of the most difficult tasks in the petroleum industry. The ability to obtain a representative sample rests in the knowledge of when the water is uniformly dispersed in the flowing hydrocarbon stream.

Although mixing elements such as bends and pipeline configurations are often counted on to provide sufficient turbulent mixing to insure representative sampling, they have not been studied thoroughly. This paper summarizes the effect of vertical upflow after one right-angle bend, vertical downflow after three right-angle bends and horizontal flow after one right-angle bend.

Previous attempts to find the conditions required for adequate dispersion in two-phase liquid–liquid flow have not been complete nor accurate. There is a range of operating velocities and configurations, common to pipeline operations, where no information on dispersion is available. As a result of these incomplete studies an estimate of the quantity of unmeasured water in crude oil was found by Hanzevack *et al.* (1980) and Berto (1982) to be 0.2–0.3%. Since crude oil is purchased on a dry basis, this unmeasured water can mean tens of thousands of dollars in overpayments for a typical marine vessel. Furthermore, these studies involved only horizontal pipeline flows and data on vertical pipeline have yet to be reported. The theory available on two-phase liquid–liquid flow is only applicable for flows in horizontal pipelines.

Proposed theoretical developments do not contain measurements of several important parameters, such as maximum water drop size, drop size distribution, energy dissipation of piping elements and the interactive effects of piping elements. These parameters are important because they control drop dispersion and more importantly the droplet settling. This research has successfully measured the maximum droplet size (d_{99}), droplet distribution and concentration profiles in straight pipe flow and in three other piping configurations. This experimental data will be incorporated with future work already in progress, studying the effects of pipe diameter and fluid physical properties. Then a complete theory for two-phase liquid–liquid pipeline flow can be developed which will predict sampling locations for adequate dispersion, and the economic penalty of using current procedures could be reduced.

METHOD

To answer the question of conditions required for water dispersion in oil, a new technique is employed which, unlike the previous ones, is unobtrusive, objective and can produce data quickly and accurately. This technique employs a computer-based image processing system.

The sediment and water found in crude oil tend to settle in stationery tanks because of their larger densities. At low bulk velocities this density difference also causes water in the hydrocarbon to flow near the bottom of a horizontal pipe. As the bulk velocity is increased, turbulent mixing and mixing elements break the water into smaller droplets which are more readily dispersed at different elevations in the horizontal pipe. When the relative concentration of water across the pipe diameter is approximately constant (i.e. does not deviate below 0.95 at the top of the pipe or above 1.05 at the bottom of the pipe), the flow regime is considered to be adequately dispersed and suitable for sampling. These water concentration profiles are the primary results of this research.

A fluid flow rig was designed by Powers (1986) for this project which is able to simulate industrial situations. Two 3740 liter carbon steel tanks are used to feed and receive bulk kerosene flow. The size of these tanks allows measurements to take place for several minutes. Kerosene was chosen as the continuous phase primarily because of its transparency. The physical properties of kerosene at 20°C, namely

density	39.5–42°API, 782 kg/m^3
kinematic viscosity	1.5 cSt
index of refraction	1.47
interfacial tension	0.032 N/m,

allow the simulation of flow fields commonly found in field scale petroleum related operations. Kerosene is pumped through a 8.2 cm i.d. PVC pipeline with attainable velocities up to 2.6 m/s. An optically flat acrylic viewing cell is included in the pipeline, to avoid light reflection from the pipe curvature, for data acquisition. A very dilute mixture of water–latex paint is injected into the center of the pipeline in the direction of the flow, at approximately the same velocity as the bulk flow. The injection is done after the mainline pump, upstream from the viewing cell.

Light from the pulsed dye laser is spread by a cylinder lens and is positioned by mirrors to the location of interest in the pipe through the viewing cell. The camera is positioned orthogonal to both the flow and the laser beam. The camera and the laser are both controlled by an image processing computer. Figure 1 shows part of this experimental setup.

The intensity distribution of light reflected by the water drops is measured by an array of sensors, 480 × 380 picture elements (pixels). Each pixel contains a gray level value from 0 to 255. This intensity distribution is then stored in a computer as a set of gray levels.

The original image is transformed to a binary image of 0s and 1s. To generate this binary image an appropriate threshold value must be chosen. Any pixel with a gray level value above this threshold is given a value of 1, and any pixel with a gray level value below this threshold is given

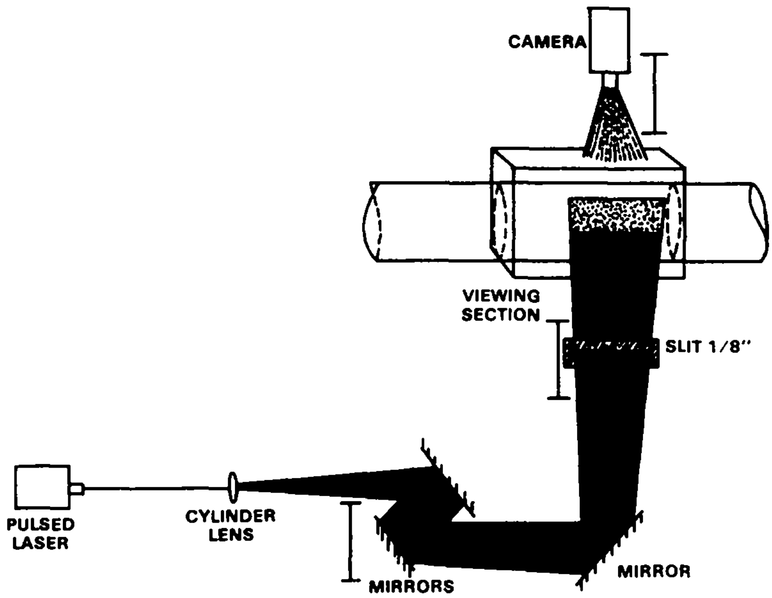


Figure 1. Experimental setup.

a value of 0 (0 meaning background and 1 meaning water drop). Unlike the ordinary photographic techniques previously employed by other researchers to measure drop sizes, software developed by Ju (1987) is employed to objectively obtain this threshold value.

The procedure to determine water concentration and drop sizes is as follows:

1. A laser image is captured and stored in the computer.
2. A threshold value is objectively chosen to convert this image to a binary image.
3. All drop candidates are labeled.
4. Candidate drop diameters and areas are determined and a series of checks are performed to screen out non-drops.
5. Drops that are very faint with respect to other drops are assumed to be drops out of the control volume, and they are eliminated.
6. The diameters and volumes of the screened drops are calculated.
7. A possibility factor for drops partially in the viewed control volume is applied.
8. All drops with comparable diameters are grouped together for drop size distribution summaries.
9. The local concentration at each pipe position is determined for that image.
10. Steps 1–9 are repeated to obtain many images at the same flow conditions. Sufficient repetitions are obtained to insure that the actual relative concentration is determined with 95% confidence. It has been verified in a separate study that this requires approx. 16 images.
11. Concentration data at each pipe position are averaged and used to generate curves to represent the water concentration profiles at a particular velocity and configuration studied.
12. A mass balance is performed as a cross check to try to account for all of the water injected into the system.

The two main limitations to this image processing technique are that it is not applicable to very small drops or very high water concentration. The technique is limited to drops with diameter > 0.063 mm. As can be seen later the mass balance was not possible for the vertical downflow configuration, due to the very fine drop size distribution attained. Another limitation of this technique occurs in positions where water concentration is very high ($\gtrsim 4.0\%$). The software did not produce absolute concentration results for several high water concentration images collected after one horizontal bend. Nevertheless, meaningful relative concentration information was extracted for these conditions, as discussed later.

RESULTS AND ANALYSIS

There are four parts to this results section. First, drop size distribution is discussed. Second, some qualitative observations are presented for water stratification conditions occurring at very low velocities. Third, water dispersion as a function of bulk velocity is discussed for several pipeline configurations commonly used in industry: a straight horizontal pipe; upflow after one bend; horizontal after one bend; and downflow after three bends. Figure 2 shows the relative pipeline configurations studied. Finally, the same data are discussed from the viewpoint of dispersion as a function of pipeline configuration, holding velocity constant. The few figures presented in this paper are selected to provide the most pertinent results.

Drop Size Distribution

Although the primary results of interest in this work are concentration profiles, some insight can be achieved by examining drop size distributions. As degree of turbulence is increased, either due to increasing velocity or additional pipeline elements (e.g. bends), a smaller drop size would be expected. This has been verified experimentally.

There are three ways to characterize drop size, first as a distribution function over the whole range of sizes, second as a population distribution and third as a maximum drop size as a function of bulk velocities for all configurations studied. It was previously reported that for a straight horizontal pipe, a Rosin–Rammler (1933) drop size distribution equation,

$$V = \exp\left(-2.996\,\frac{d}{d_0}\right)^n,$$

adequately characterizes the experimental data for any velocity. In this equation V is the cumulative volume fraction of droplets with diameter greater than d, d is the droplet diameter, d_0 is an arbitrary normalizing drop diameter and n is a constant. This is in agreement with the findings of Karabelas (1978). It has now been determined that the Rosin–Rammler function is also valid for the various pipeline configurations studied. This information will be instrumental in future theoretical modeling studies. A graphical representation of this function for all the configurations and velocities studied in this research was developed, and based on the slope of the curve the exponent n was calculated. As an example of this function figure 3 illustrates the validity of the

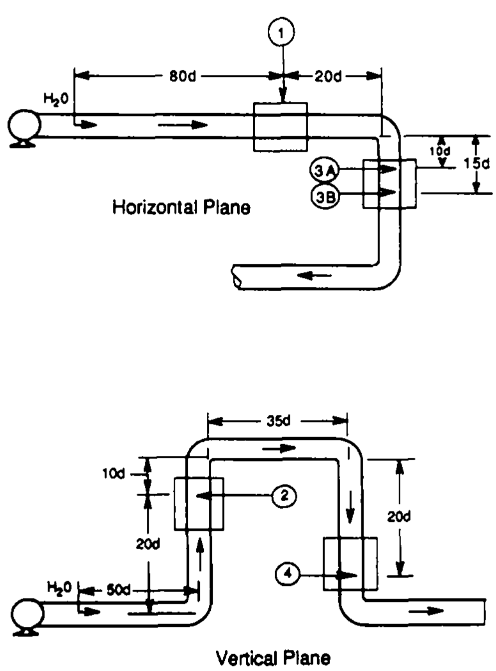


Figure 2. Relative position of the pipeline configurations studied.

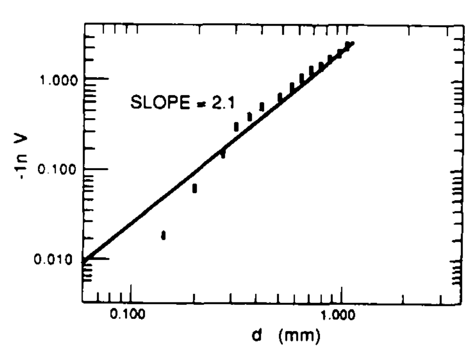


Figure 3. Drop size distribution at 2.24 m/s, for vertical downflow after the three bends configuration represented by a Rosin–Rammler function.

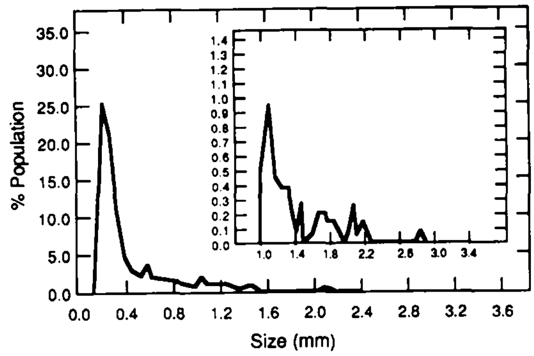


Figure 4. Drop size distribution at 1.44 m/s for the straight horizontal pipeline flow configuration.

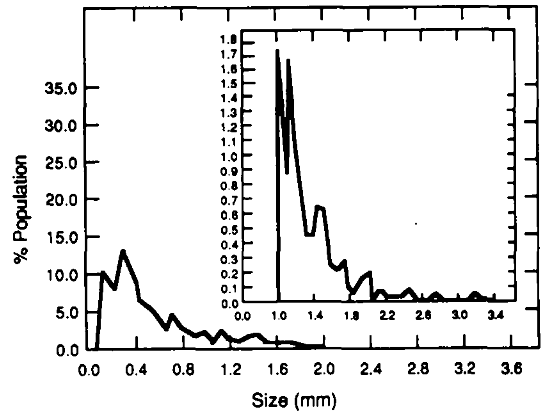


Figure 5. Drop size distribution at 1.35 m/s for vertical upflow after the one bend configuration.

Rosin–Rammler function for downflow after three bends at 2.2 m/s velocity. Table 1 summarizes the exponents found in this research for all the configurations studied.

Figures 4–7 illustrate the percentage population distribution for some selected velocities and configurations to show the effect of bends and velocity on drop size. The inset graphs show the percentage population of large drops on a larger scale. Clearly the drops for the downflow after the three bends configuration are very small, whereas for the other configurations bigger drops are in the population distribution. Although the number of bigger drops appears to be small relative to the number of small drops, a few larger drops can be responsible for most of the concentration.

A simpler measure of drop size distribution for the configurations studied is the maximum drop diameter, d_{max}. Actually, d_{99} is used to avoid statistical aberrations caused by a single large drop; d_{99} is the drop diameter such that 99% of all the drops have a smaller diameter than this value. Figure 8 shows d_{99} vs velocity for the straight horizontal, vertical upflow and downflow configurations. There are two significant features of the graph, the effect of velocity and the effect of pipeline bends. First, figure 8 shows a slight tendency toward decreasing drop size with velocity. Secondly, the effect of pipeline bends can be considered. Figure 8 shows that one bend does reduce the maximum drop size more than the straight horizontal case. Three bends in succession leads to even smaller drops. Clearly the interaction of several bends is helpful to achieve smaller maximum drop size.

Qualitative Observations at Very Low Velocity

Qualitative observations are presented for the water stratification conditions occurring at very low velocities. Quantitative data at these conditions were not collected since it was immediately obvious that they would not provide adequate dispersion for representative sampling. However, the qualitative observations are given to provide additional insight into the physical phenomena involved. This part of the research was done to establish a minimum velocity for the vertical upflow

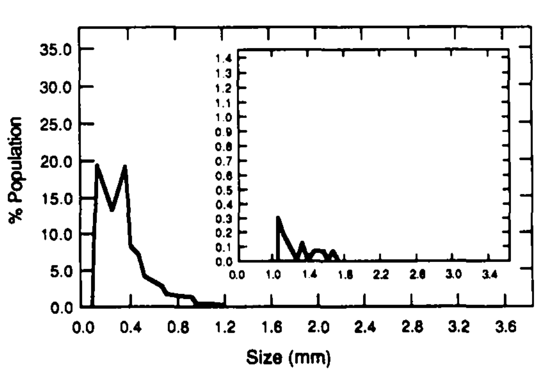


Figure 6. Drop size distribution at 1.35 m/s for vertical downflow after the three bends configuration.

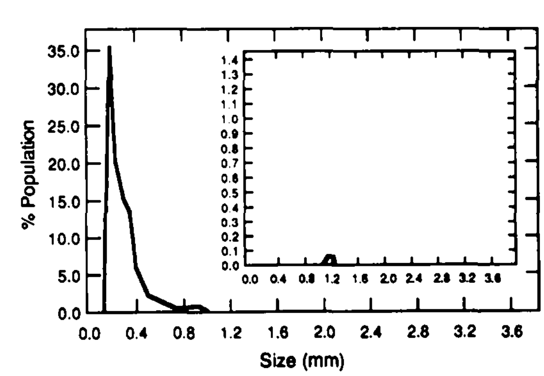


Figure 7. Drop size distribution at 2.24 m/s for vertical downflow after the three bends configuration.

Table 1. Rosin–Rammler exponents

Configuration	Velocity (m/s)	n
	1.0	2.1
Straight horizontal flow	1.4	1.9
	2.2	2.1
	2.4	2.1
Vertical upflow after one bend	1.3	2.1
	1.7	2.1
	2.2	2.3
Vertical downflow after three bends	0.8	2.5
	1.3	2.1
	2.2	2.1

and downflow configuration at which data could be collected and analyzed with confidence. Figure 9 shows a qualitative analysis and the observations for these very low velocities. All comments in this section are based on visual observation, not measurements.

Six locations in the pipeline were studied at three different velocities. At 0.2 m/s bulk velocity there are no drops present. The water accumulates at the lower part of the horizontal pipe creating a distinct film. As seen from the figure, at location A the drops have not risen to the vertical section of the pipeline. Representative sampling is not possible under these conditions at any location of the pipeline.

At 0.4 m/s water accumulates at the lower part of the pipe with drops above the film which tend to escape into the bulk flow at location B. At location C of the pipeline big drops swirl and smaller drops rise in a pulsed manner to the top. At section D at the second elbow the drops recombine to form bigger drops and fall back down to sections D and C. In the horizontal elevated section

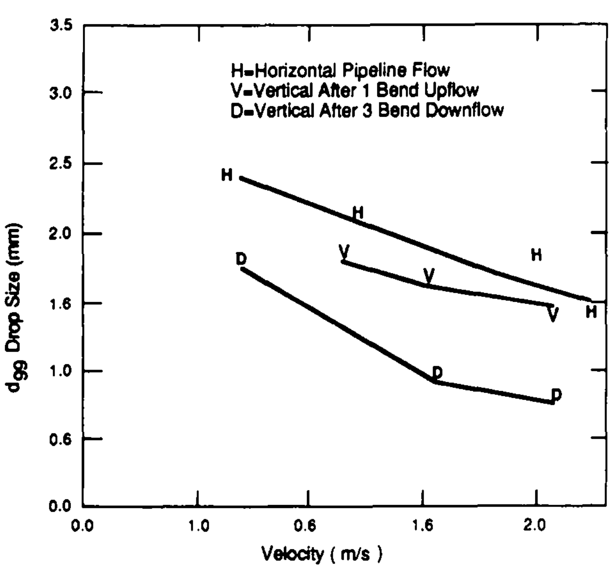


Figure 8. d_{99} Drop size vs velocity for different pipeline configurations.

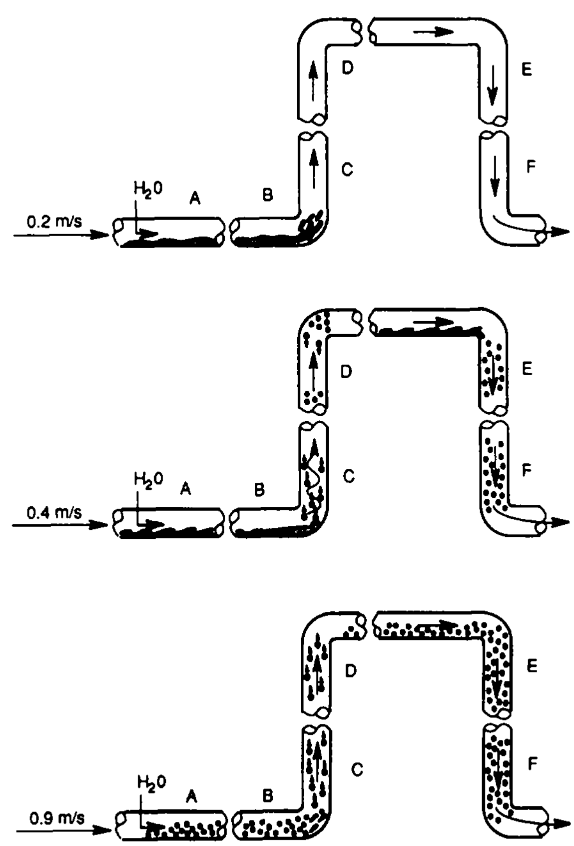


Figure 9. Kerosene–water two-phase flow regimes at low velocities.

of the pipeline the drops accumulate at the lower section of the pipe and fall to section E. At the upper right section of location E, there were no drops present. At about 4 diameters from the bend the drops flow downwards uniformly. At section F, the drops become smaller and water droplets appear to be well-dispersed. Although not ideal, there is a reasonable chance of collecting representative samples in the downflow section, location F.

At 0.9 m/s bulk velocity, big drops accumulate at the lower section of pipe position A. At position B, the drops cover half of the pipe's cross-sectional area and rise in a pulsed manner, swirling to section C up to about 10 diameters from the bend, then rising to section D. At the upper horizontal section of the pipeline, the drops are again stratified. At section F, the drops swirl at the bend and continue, apparently relatively dispersed, down to section E. The drop size at section F appears to be considerably smaller than the drops in section D, and considerably smaller than the drops at the same location F at 0.9 m/s. The upflow leg, near the top, provides some chance of representative sampling. However the downflow leg, near the bottom, seems to provide the best sampling location at this velocity, both from a standpoint of smaller drop size as well as relatively uniform concentration profile.

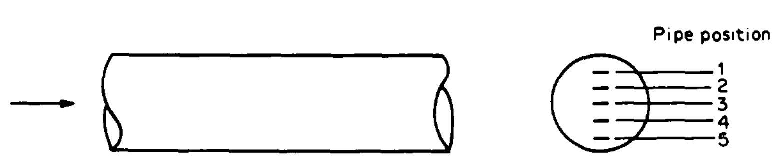
Concentration Profiles: Effect of Velocity At Various Pipeline Configurations

Straight horizontal pipeline flow

Concentration profile data were collected in a long straight horizontal pipe by Bowers (1986) and Hanzevack & Bowers (1988) 80 diameters from the water injection point. The relative concentration or water fraction, defined as the experimentally determined water concentration divided by the original water concentration injected, at this configuration for all velocities studied is shown in table 2. In this table the Reynolds and Weber numbers are shown as well. The relative concentration is shown in figure 10 as a function of velocity. A transition region from stratified to adequately dispersed flow is shown to occur at about 2.1 m/s velocity, and at 2.4 m/s the flow is in the dispersed regime.

Table 2. Horizontal pipeline flow: water fraction at five pipe positions as a function of velocity

Velocity (m/s)	Re	We	Pipe position	Average fraction
			1	0.30
			2	0.20
1.0	48,000	2400	3	0.49
			4	0.66
			5	3.81
			1	0.60
			2	0.61
1.4	68,000	4800	3	0.96
			4	1.16
			5	2.72
			1	0.68
			2	0.93
2.2	102,000	10,900	3	1.15
			4	1.07
			5	1.38
			1	0.93
			2	1.07
2.4	113,000	13,300	3	0.91
			4	1.15
			5	1.06



Even though adequate dispersion for this configuration is achieved at about 2.3 m/s, it is often economically impractical to use this velocity for sampling; therefore other configurations were studied, and adequate dispersion was achieved at lower velocities.

Vertical upflow after one bend

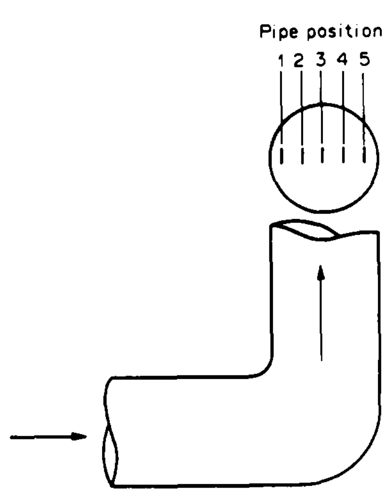
Concentration profile data were collected in the upflow leg of a vertical loop, 70 diameters from the water injection point and 20 diameters downstream from the right-angle bend. The velocities studied at this configuration are 1.3, 1.7 and 2.2 m/s. The relative water concentration at this location for all velocities studied is shown in table 3. Position 1 is the position across the pipe diameter closest to the camera, at the outside of the loop. Figure 11 is a plot of this relative concentration vs pipe diameter position. This plot shows that dispersion may not be a simple function of velocity, as it was in the case for horizontal pipeline flow. This may be due to swirling observed after one bend and to the energy dissipation effect on the bend being greater than the velocity effect.

Horizontal flow after one bend

Concentration profile data were collected for this configuration at 105 diameters from the water injection point, 10 diameters downstream from the right-angle bend. The velocities studied for this configuration are 0.8, 1.6 and 2.3 m/s. At 0.8 m/s the flow was stratified and the mass balance checked. For the other two velocities the mass balance did not check, and the degree of swirling was observed to increase with velocity. To understand why the mass balance does not check, some supplementary data were collected across a horizontal plane through the center of the pipe, at

Table 3. Vertical upflow after one bend: water fraction at five pipe positions as a function of velocity

Velocity (m/s)	Re	We	Pipe position	Average fraction
			1	1.38
			2	1.32
1.3	64,000	3000	3	1.03
			4	0.72
			5	0.93
			1	1.09
			2	1.35
1.7	79,000	4600	3	0.90
			4	0.73
			5	0.92
			1	1.09
			2	1.65
2.2	106,000	8400	3	0.86
			4	0.83
			5	0.63



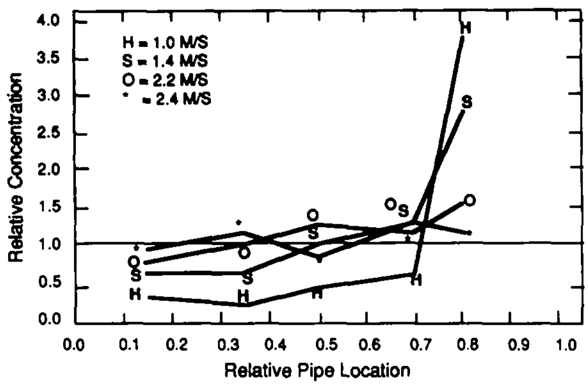


Figure 10. Relative water concentration as a function of velocity for straight horizontal pipeline flow.

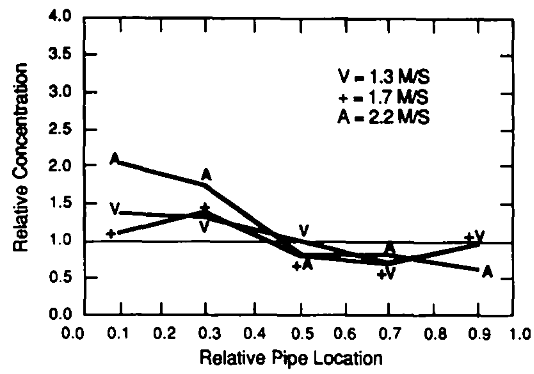


Figure 11. Relative water concentration as a function of velocity for the vertical upflow configuration.

1.6 m/s. To see the effect of the bend on the average relative concentration, supplementary data were also collected at 15 diameters downstream from the horizontal bend. The relative concentrations are presented in table 4, with position 1 near the top of the pipe.

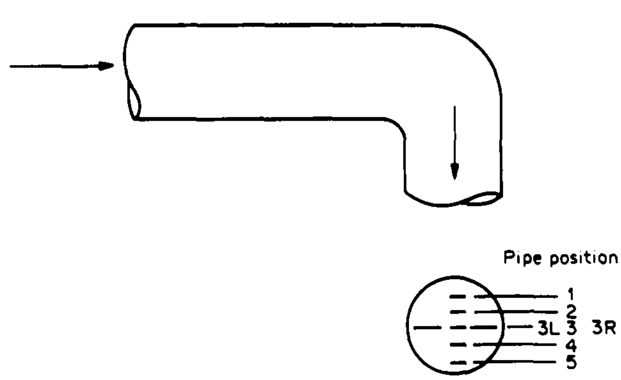
For the 10 diameters downstream from the bend configuration at 0.8 m/s bulk velocity, the flow is stratified. At higher velocities the water drops swirl, producing uniform fractions at the five positions, but at higher relative concentrations. There are two basic explanations for this relative

Table 4. Flow after one horizontal right-angle bend: water fraction at different pipe locations as a function of velocity

Velocity (m/s)	Re	We	Pipe position[a]	Average fraction	
			1		0.39
			2		0.87
0.8	40,000	1 200	3		1.03
			4		2.36
			5		2.04
				(1)[b]	(2)[b]
			1	1.89	5.14
			2	4.12	1.29
1.6	79,000	4 600	3	3.83	7.18
			4	3.62	3.95
			5	2.80	3.50
			3L	6.14 (L)	
			3R	3.02 (R)	
			1		2.44
			2		4.08
2.3	109,000	8 400	3		4.78
			4		2.05
			5		1.08

[a]Where 3 is the center position, 3L and 3R are positions left and right of 3 with respect to the flow direction.

[b](1) Water fraction at 10 diameters from the bend; (2) water fraction at 15 diameters from the bend.



water concentration. First the assumed relative velocity of 1.0 used in the software to calculate relative water concentration, and check the mass balance, is no longer valid for this configuration. Drops lose their kinetic energy due to swirling and due to the wall of the bend. Second, the images taken for this configuration appeared with unusually large and many drops in the control volume. For these images, the background for image processing analysis is no longer kerosene, but water, and it is difficult to obtain a convincing threshold value accurately. The other positions for this configuration are affected in the same way.

Vertical downflow after three bends

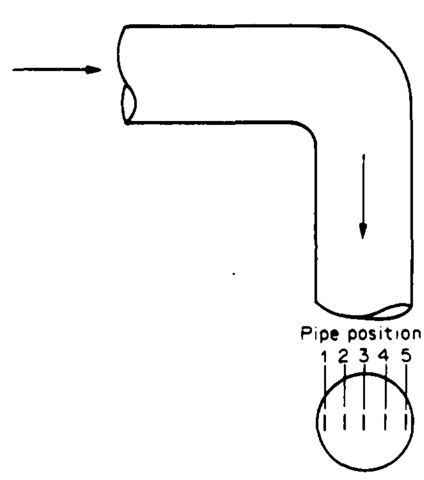
The final pipeline configuration studied is in a vertical downflow position after three consecutive right-angle bends. The concentration profile data collected for this configuration are 135 diameters from the injection point and 20 diameters downstream from the third bend. The bends are approx. 30 diameters apart.

For this configuration, the initial relative water concentration was found to be very small. This is due to most of the drops being < 0.06 mm so the camera is unable to detect them. When magnification is applied (25.5 pixel/mm vs 15.9 pixel/mm) at position 1 (position 1 is the one closest to the camera in the inner loop), the smaller drops were detected and the relative water concentration was improved. This additional drop breakup, although causing experimental difficulties, is clearly desirable from a representative sampling viewpoint.

Three velocities were studied for this configuration, 0.8, 1.3 and 2.2 m/s. The relative water concentration at five positions is presented in table 5 and a normalized graph is shown in figure 12.

Table 5. Vertical downflow after three bends: water fraction at five pipe positions as a function of velocity

Velocity (m/s)	Re	We	Pipe position	Average fraction
			1	0.47
			2	0.40
0.8	40, 000	1 200	3	0.48
			4	0.40
			5	0.44
			1	0.18
			2	0.17
1.3	64, 000	3 000	3	0.13
			4	0.15
			5	0.15
			1	0.24
			2	0.22
2.2	106, 000	8 400	3	0.14
			4	0.17
Magnified position (25.5 pixel/mm)			1	0.73



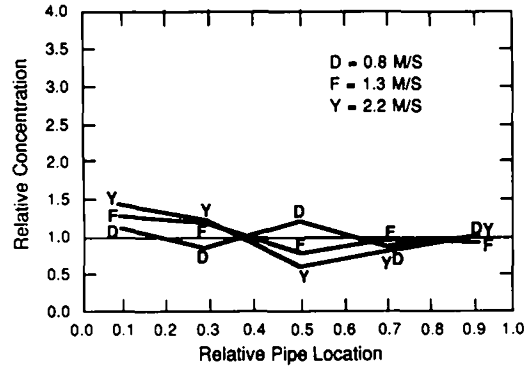


Figure 12. Relative water concentration as a function of velocity for the vertical downflow configuration.

Clearly this configuration provides adequate dispersion and is best for oil–water sampling even at 0.8 m/s. The reduced drop size and improved dispersion indicate that the bends were close enough to be interactive. Non-interactive bends would not have the same effect. Unfortunately, however, there are no generally accepted guidelines for predicting how close bends must be to be interactive.

Concentration Profiles: Effect of Pipeline Configuration at a Given Velocity

This same concentration profile data can be viewed from a different perspective by plotting results obtained at the same or similar velocity for different pipeline configurations. This work indicates that the number of interacting upstream bends is a significant factor in dispersion. Figures 13 and 14 show the concentration profile data in this manner.

Figure 13 shows that at approx. 1.3 m/s the straight horizontal pipe still results in obvious stratification, while vertical flow after one bend results in some swirling. Downflow after three bends again provides adequate dispersion.

Figure 14 shows that at approx. 2.3 m/s vertical or horizontal flow after only one bend still show evidence of swirling. Either the straight horizontal pipe or vertical flow after three bends both provide adequate dispersion. These results are valid for the pipeline size used in this study. They cannot be scaled up directly to field size pipe until the effect of pipeline diameter size is studied.

CONCLUSIONS

Drop size distributions have been measured at several velocities for four different pipeline configurations. The drop size distribution decreases with increasing velocity and number of bends. These drop size distribution data were shown to follow a Rosin–Rammler power law. The recommended Rosin–Rammler exponent, based on this work, is $n = 2.0$ for the straight horizontal

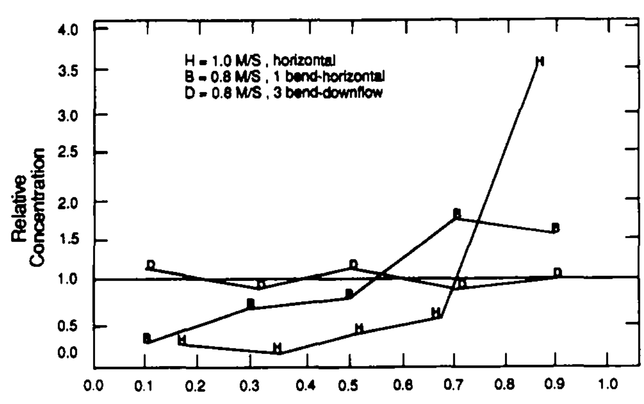


Figure 13. Relative water concentration for different configurations at low velocities.

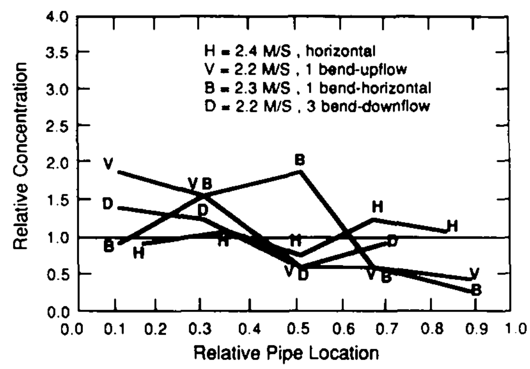


Figure 14. Relative water concentration for different configurations at high velocities.

pipe, $n = 2.1$ for vertical upflow after one bend and $n = 2.1$ for vertical downflow after three bends. These values are similar to the values found by Karabelas (1978), 2.0–4.0.

The concentration profile data collected has demonstrated that, as velocity is increased, there is a transition from stratified to adequately dispersed flow in the straight horizontal pipe. This transition to the dispersed regime occurs at approx. 2.3 m/s. However, the data for the current study were collected in a 8.2 cm dia pipe. Additional work at different pipeline diameters is needed before prediction of a transition velocity can be generalized.

After one right-angle bend, either in the horizontal or vertical plane, there is considerable swirling. This swirling is most pronounced near the bend. Adequate dispersion is not usually achieved; therefore, sampling after one bend is not recommended.

Adequate dispersion is achieved in downflow after three bends at a lower velocity than for a straight horizontal pipe, in this case at 0.8 m/s.

FUTURE WORK

Future work already in progress will be examining the effect of pipe diameter and fluid physical properties on dispersion of water in hydrocarbons. The results of this work can be used along with the results presented in this paper to develop a theoretical model which will predict water–hydrocarbon dispersion as a function of all the major parameters involved.

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