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AN EXPERIMENTAL STUDY OF THREE-PHASE FLOW REGIMES

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Abstract—Three-phase flow regimes for an air/water/oil system flowing in a horizontal pipe line were observed and flow regime maps were constructed. Superficial velocities, ranging from 15 to 5000 cm/s for air (j_a) and from 0.4 to 66 cm/s for water (j_w), were investigated. The superficial velocity of the immiscible oil "phase" (j_o) was kept constant at three discrete values, 4.3, 9 and 24 cm/s. Water- and oil-based wavy, plug, slug and stratifying-annular flow regimes were observed. Many interesting new flow regime configurations not seen in two-phase flow were found.

Key Words: three-phase flow, flow regimes

INTRODUCTION

There have been numerous investigations of two-phase flow regimes, in contrast, three-phase flow regimes have not been studied thoroughly. Because of the abundance of three-phase flow applications in the petroleum and chemical industries, a better understanding of this complex flow phenomena is needed. The most important application of three-phase flow is in the undersea oil well lines used for off-shore petroleum recovery. These lines lie at the bottom of the sea in horizontal and near-horizontal positions, and may contain a three-phase mixture of crude oil, sea water (occurring naturally in the reservoir or injected during production to maintain the reservoir pressure) and natural gas flowing through them. The pressure drop and stability characteristics of the flow in these lines are important to the proper operation of off-shore oil well platforms, and they depend intimately on the flow regimes that occur.

There is only a limited amount of previous work on three-phase flows published in the field. In an early study of three-phase flow, Tek (1961) treated the two immiscible liquid "phases" as a single fluid with mixture properties to provide a correlation for pressure loss predictions. Later, Galyamov & Karpushin (1971) considered the liquid phases separately and found that the effective viscosity of the mixture was a function of the liquid volume fraction. Foreman & Woods (1975) treated the gas phase separately from the liquids. Subsequently, Shean (1976) developed flow regime maps and applied drift-flux techniques to vertical three-phase flow in pipes.

In addition, Govier & Aziz (1972) presented flow regime maps for horizontal liquid/liquid flows, however they did not consider a gas phase. Bhaga & Weber (1972) analyzed vertical gas/liquid/solid flows for average volumetric fractions by using one-dimensional drift-flux theory. They supported their analytical results with the experimental data they obtained, however, no flow regime maps were proposed. Subsequently, Giot (1982) analyzed vertical gas/liquid/solid flows and his models gave a good prediction of the volumetric fraction of the phases and the frictional pressure drop for data taken in various pipe diameters (from 40 to 300 mm).

DESCRIPTION OF THE EXPERIMENTAL APPARATUS

The three-phase flow data presented herein were taken in the test loop shown schematically in figure 1. Air and water were used as two of the phases and mineral oil was used as the third "phase". The mineral oil has properties similar to common light liquid hydrocarbons (e.g. North Sea crude oil). In particular, it had a viscosity ($\mu = 0.1164$ Ns/m^2 at 25°C) which was approx. 116 times higher than that of water at STP and a density of 864 kg/m^3, which is 86.4% of that for water at STP.

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Special care was taken to keep the i.d. constant at 19 mm in the copper tubes, ball valves, Plexiglas tubes and the connections and unions which comprised the horizontal test rig. The Plexiglas tubes that were used in the flow development section ($L/D = 154$) and the test section ($L/S = 96$) made visual observations possible. A flow development length of 154 L/D was determined to be sufficient to obtain fully developed flow for the flow regimes investigated in these experiments. This was verified by rotation of the mixing tee and by changing the relative location of the fluid injection. For the flow development length used ($L/D = 154$), the flow regimes were not affected by these changes, thus verifying that fully developed flow had been achieved.

There was also an exit section following the test section ($L/D = 54$) to minimize end effects. The entrances, test and exit sections were mounted on an I-beam that was pivoted at the middle and supported at the ends, in this way the flow angle from horizontal could be easily varied. However, in the data presented herein, the I-beam was held horizontal.

A phase separation tank, which was vented to the atmosphere, was located at the end of the test section. This tank served two objectives: elimination of back-pressure and separation of the air from the liquid phases. A temperature sensor was placed in the separation tank to observed the temperature of the liquid mixture. The liquid phases were accumulated in a collection tank (0.4 m^3 in capacity) and pumped to a large settling tank with a centrifugal pump. The required time for the liquids to be completely gravity separated in the 2.7 m high settling tank was approx. 6 h. After gravitational separation, the water and oil were pumped to separate storage tanks (75 l. each in volume) using a centrifugal water pump and a positive displacement oil pump.

During the experiments, water and oil were pumped from the storage tanks through heat exchangers and rotameters to the three-phase mixer shown in figure 2. Water and oil temperatures were kept constant at $26 \pm 0.5°C$ by adjusting the flow rate of the cooling water in the heat exchanger shown in figure 1. One of two parallel-connected Dwyer rotameters for each liquid phase were used for volumetric flow rate measurements; very stable flow rates were achieved by using the throttling valves in the rotameters. Air was supplied at a constant pressure of 414 kPa, and

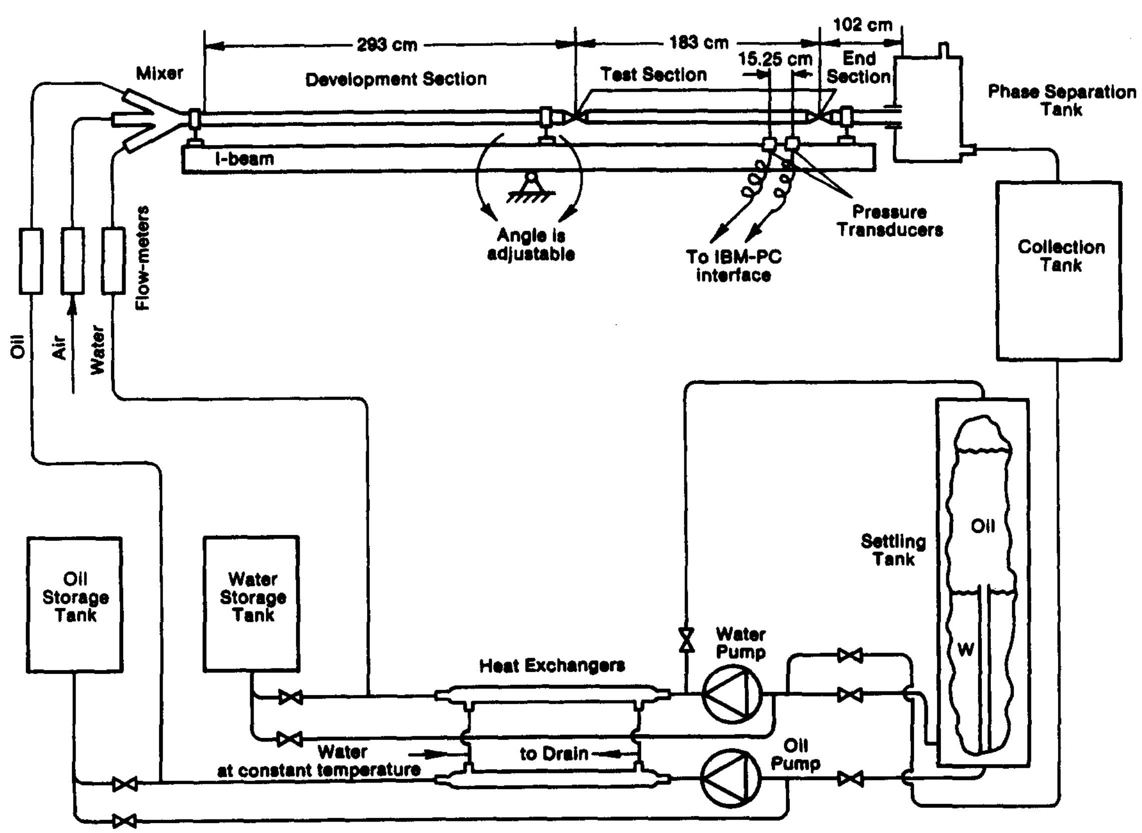

Figure 1. Three-phase flow loop.

was routed into the mixer through one of four parallel-connected Dwyer air rotameters; its flow rate was adjusted using throttle valves in the flow meters. Absolute air pressure was recorded for each data point using a pressure gauge at the outlet of the air flow meters. Absolute air pressure was also recorded at the beginning of the test section using a set of calibrated Validyne variable-reluctance transducers which were connected to an IBM XT computer through a Carrier demodulator and an analog/digital converter. The pressure tap was mounted flush on the pipe wall and was linked to pressure transducers through short tubing and a valve. The appropriate diaphragms for the transducers were selected according to the pressure level to obtain the maximum resolution possible for each flow condition. Both of these pressure readings were used to calculate the air flow rates in the test section. A copper tube (1.27 cm i.d.), was used to deliver air to the three-phase mixer via rotameters. As in the liquid phase lines, this copper tube was connected to a braided rubber hose that served the purpose of damping pressure fluctuations before the phases entered into the mixer. Air, oil and water were combined in the three-phase flow mixer shown in figure 2. This mixer was built in such a way that the initial base phase (i.e. the phase having the largest volume fraction) and the initial bubble/drop sizes for the other phases could be chosen. During calibration runs it was verified that neither the orientations of the mixer, nor the location of the air/water/oil inlets affected the data in the test section (i.e. fully developed conditions were achieved).

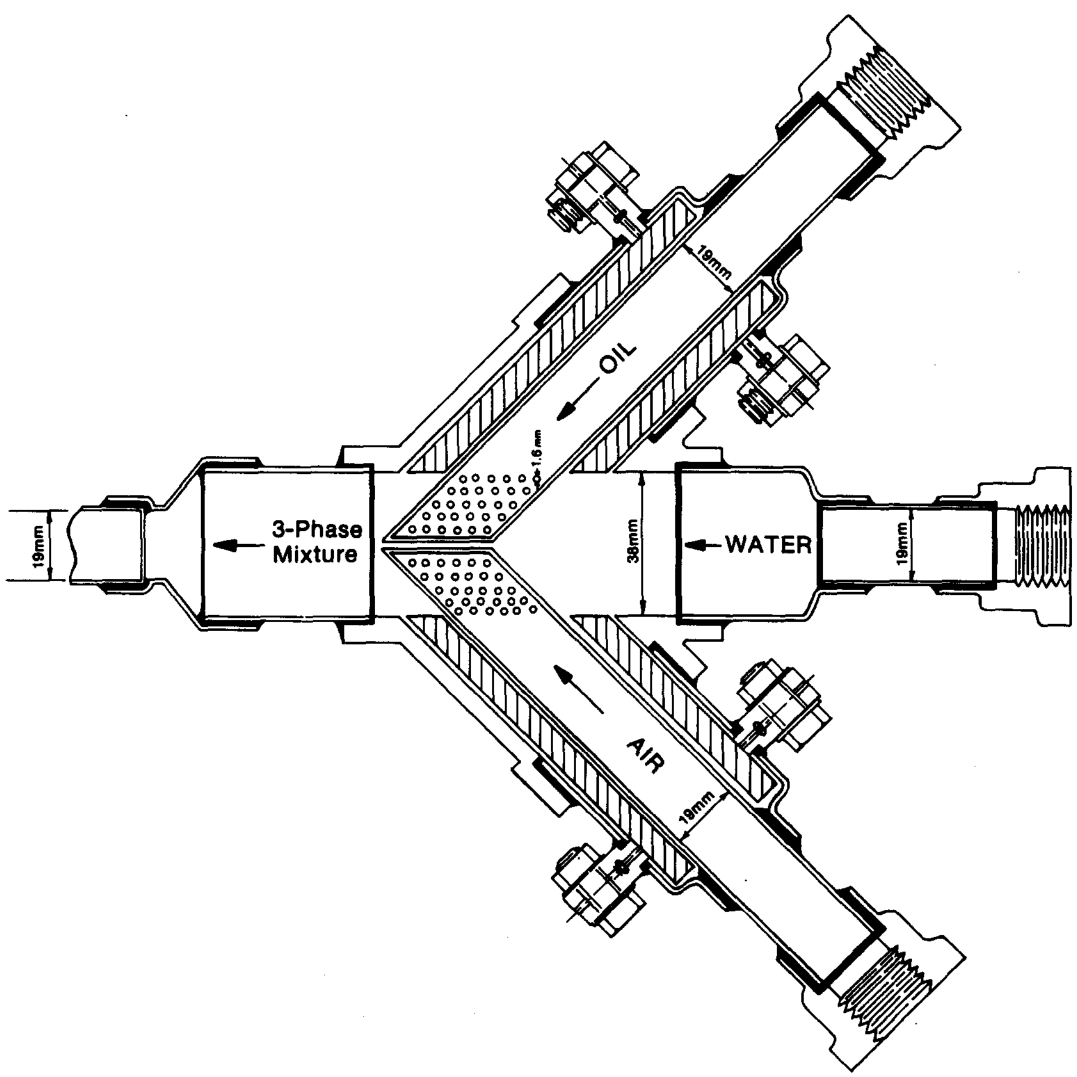

Figure 2. Oil/water/air mixer (plan view).

Table 1a. Flow regime data: base transition data

Superficial water velocity, j_w (cm/s)	Superficial air velocity, j_a (cm/s)	Superficial oil velocity, j_o (cm/s)
1.32	20	4.3
1.43	40	4.3
1.21	60	4.4
1.12	80	4.3
1.15	100	4.3
2.15	200	4.3
2.91	300	4.3
3.06	500	4.3
2.73	700	4.3
2.12	1000	4.3
1.27	2000	4.3
1.08	3000	4.3
0.92	5000	4.3
6.94	20	9.0
5.44	40	9.0
4.09	60	9.0
2.82	80	9.0
2.04	100	9.0
3.22	200	9.0
4.25	300	9.0
4.43	500	9.0
4.27	700	9.0
4.02	1000	9.0
2.33	2000	9.0
1.98	3000	9.0
1.38	5000	9.0
12.31	20	24.0
9.93	40	24.0
8.86	60	24.0
7.92	80	24.0
6.10	100	24.0
7.94	200	24.0
10.19	300	24.0
9.89	500	24.0
9.05	700	24.0
7.08	1000	24.0
3.86	2000	24.0
2.74	3000	24.0
2.08	5000	24.0

Table 1b. Flow regime data: data for oil-based flow regime transition boundaries

Superficial water velocity, j_w (cm/s)	Superficial air velocity, j_a (cm/s)	Superficial oil velocity, j_o (cm/s)	Flow regime transition between
0.4	14.41	4.3	1 and 2
0.6	14.37	4.3	1 and 2
0.8	14.22	4.3	1 and 2
0.4	115.00	4.3	2 and 5
0.6	113.00	4.3	2 and 5
0.8	110.00	4.3	2 and 5
0.4	312.00	4.3	5 and 6
0.6	334.00	4.3	5 and 6
0.8	365.00	4.3	5 and 6
1.2	301.00	4.3	3 and 4
2.0	307.00	4.3	3 and 4
1.32	200.00	4.3	3 and 5
1.07	300.00	4.3	4 and 5
0.96	500.00	4.3	4 and 6
1.06	1000.00	4.3	4 and 6
0.4	20.1	9.0	1 and 2
0.8	20.3	9.0	1 and 2
2.0	19.8	9.0	1 and 2
0.4	162.00	9.0	2 and 5
0.6	127.00	9.0	2 and 5
1.0	114.00	9.0	2 and 5
0.4	317.00	9.0	5 and 6
0.6	354.00	9.0	5 and 6
1.0	386.00	9.0	5 and 6
3.0	310.00	9.0	3 and 4
4.0	332.00	9.0	3 and 4
2.67	300.00	9.0	3 and 5
2.29	400.00	9.0	4 and 5
2.17	500.00	9.0	4 and 6
2.33	700.00	9.0	4 and 6
2.61	1000.00	9.0	4 and 6
1.00	30.7	24.0	1 and 2
3.00	28.3	24.0	1 and 2
6.00	25.6	24.0	1 and 2
0.4	221.00	24.0	2 and 5
1.00	186.00	24.0	2 and 5
3.00	142.00	24.0	2 and 4
0.4	363.00	24.0	5 and 6
1.0	409.00	24.0	5 and 6
3.0	421.00	24.0	5 and 6
9.0	406.00	24.0	3 and 4
10.0	409.00	24.0	3 and 4
9.0	321.00	24.0	3 and 5
6.92	500.00	24.0	4 and 6
5.89	700.00	24.0	4 and 6
5.26	1000.00	24.0	4 and 6

Table 1c. Flow regime data: data for water-based flow regime transition boundaries

Superficial water velocity, j_w (cm/s)	Superficial air velocity, j_a (cm/s)	Superficial oil velocity, j_o (cm/s)	Flow regime transition between
3.0	90.0	4.3	7 and 8
8.0	92.0	4.3	7 and 8
20.0	95.0	4.3	7 and 8
60.0	98.0	4.3	7 and 8
3.0	1085.0	4.3	8 and 9
8.0	917.0	4.3	8 and 9
20.0	809.0	4.3	8 and 9
60.0	791.0	4.3	8 and 9
3.0	1468.0	4.3	9 and 10
8.0	1512.0	4.3	9 and 10
20.0	1535.0	4.3	9 and 10
60.0	1727.0	4.3	9 and 10
4.0	98.0	9.0	7 and 8
8.0	102.0	9.0	7 and 8
20.0	105.0	9.0	7 and 8
60.0	107.0	9.0	7 and 8
5.0	904.0	9.0	8 and 9
8.0	797.0	9.0	8 and 9
20.0	686.0	6.0	8 and 9
60.0	608.0	9.0	8 and 9
5.0	1019.0	9.0	9 and 10
8.0	1026.0	9.0	9 and 10
20.0	1039.0	9.0	9 and 10
60.0	1052.0	9.0	9 and 10
7.0	113.0	24.0	7 and 8
10.0	117.0	24.0	7 and 8
20.0	121.0	24.0	7 and 8
60.0	139.0	24.0	7 and 8
7.0	1164.0	24.0	8 and 9
10.0	1047.0	24.0	8 and 9
20.0	923.0	24.0	8 and 9
60.0	817.0	24.0	8 and 9
7.0	1289.0	24.0	9 and 10
10.0	1307.0	24.0	9 and 10
20.0	1312.0	24.0	9 and 10
60.0	1326.0	24.0	9 and 10

EXPERIMENTAL PROCEDURE

The following methodology was used to construct the three-phase flow regime maps. The oil superficial velocity was kept constant for a given regime map. The water superficial velocity was then increased slowly, while keeping the air superficial velocity constant, to determine the transition point from oil- to water-based flow. A similar procedure was applied to acquire data for the flow regime transition points. However in this case, the water flow rate was held constant, while the air flow rate was varied. All data taken in this study are presented in tables 1a–1c.

CLASSIFICATION OF THE THREE-PHASE FLOW REGIMES

To our knowledge there have been no prior studies on horizontal three-phase flow regime maps, although there has been a lot of complementary work on horizontal two-phase flow regime maps. The fact that gravity forces often cause horizontal two-phase flows to be asymmetric makes establishing a common terminology on horizontal flow regimes more difficult than for vertical flows, which are symmetric. Many authors have used different definitions for horizontal two-phase flow regimes. As a consequence, it is often difficult to see consistency between the two-phase flow regime maps constructed by different researchers. Schicht (1969) compared the definitions used by various authors, and showed how they varied. Obviously, it is important to note which definitions have been used on a particular horizontal, two-phase flow regime map or data set. The same is true for horizontal three-phase flows.

In an attempt to classify horizontal three-phase flow regimes we distinguished between plug and slug flows. When the liquid phases were driving the gas phase the flow regime was classified as plug flow. In contrast, when the gas phase was the driving phase, the flow regime was classified as slug flow.

All annular flow data taken in this study was for stratifying-annular flow conditions, in which, due to stratification, the liquid film at the bottom of the conduit was thicker than at the top.

For two-phase flows, it was thought necessary by some researchers to make a distinction between ripple-wave stratified flow and disturbance-wave stratified flow (also called semi-slug flow by some authors), because of the fact that disturbance waves are a sign of incipient transition from wavy to slug flow. In our study such a distinction was deemed to be unnecessary.

In three-phase stratified flows one can have a dispersed mixture of the immiscible liquid phases. Moreover, oil-based flow regimes bring a new variety of flow regimes that do not occur in water-based three-phase flow. This fact makes new terminology for these flow regimes necessary. This terminology for oil- and water-based three-phase flows is given in table 2. Figures 3–5 show the various flow regime maps. It is interesting to note that flow regimes 3 and 4 apparently disappear as the superficial oil velocity (j_o) is increased.

DESCRIPTION OF THE THREE-PHASE FLOW REGIMES

We will begin with a consideration of oil-based flow regimes and later consider water-based flow regimes.

Table 2. Three-phase flow regime classification

Region	Flow regime
1	Oil-based dispersed plug flow
2	Oil-based dispersed slug flow
3	Oil-based dispersed stratified/wavy flow
4	Oil-based separated stratified/wavy flow
5	Oil-based separated wavy stratifying-annular flow
6	Oil-based separated/dispersed stratifying-annular flow
7	Water-based dispersed slug flow
8	Water-based dispersed stratified/wavy flow
9	Water-based separated/dispersed incipient stratifying-annular flow
10	Water-based dispersed stratifying-annular flow

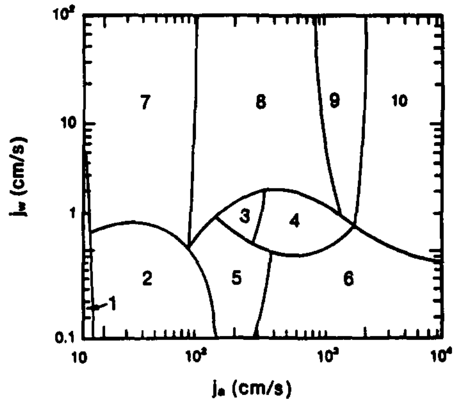

Figure 3. Three-phase flow regime map ($j_o = 4.3$ cm/s).

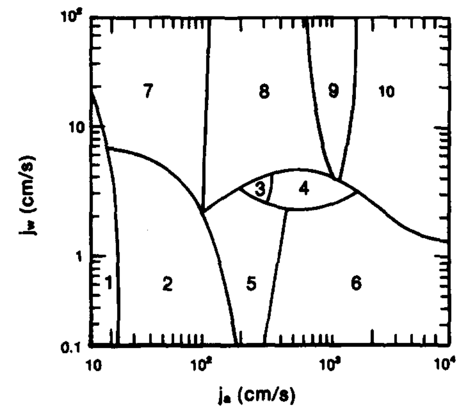

Figure 4. Three-phase flow regime map ($j_o = 9.0$ cm/s).

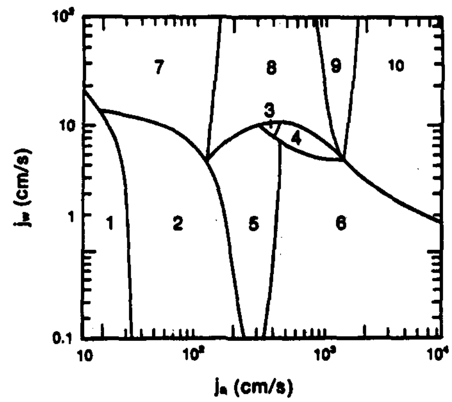

Figure 5. Three-phase flow regime map ($j_o = 24$ cm/s).

Oil-based dispersed plug flow

For relatively low water and air superficial velocities oil-based dispersed plug flow was observed. At these flow rates, water mixed with oil causing a liquid mixture which was foamy in appearance. As was discussed previously, plug flow was distinguished from slug flow. As long as the liquid phases were driving the air phase the flow regime was considered to be plug flow. Sketches of the visual observations for this flow regime are given in figure 6.

Oil-based dispersed slug flow

On increasing the air superficial velocity, it was observed that the air phase began to drive the liquid phases. This implied that we were in the slug flow regime. Sketches of this flow regime are given in figure 7. As before, in the slug flow region the oil-based liquid phase appeared to be foamy. In contrast with plug flow, however, the trailing edge of the large air bubbles was not sharply defined.

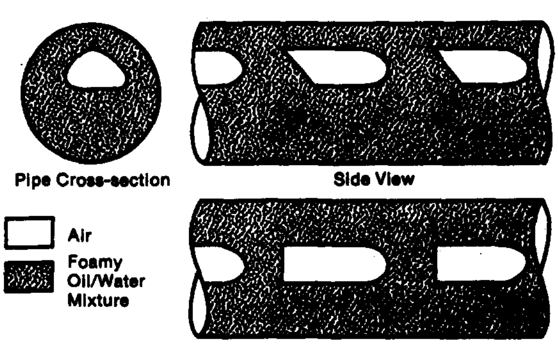

Figure 6. Schematic diagram of oil-based dispersed plug flow (region 1).

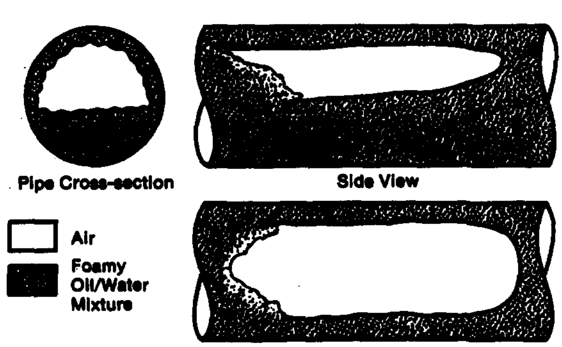

Figure 7. Schematic diagram of oil-based dispersed slug flow (region 2).

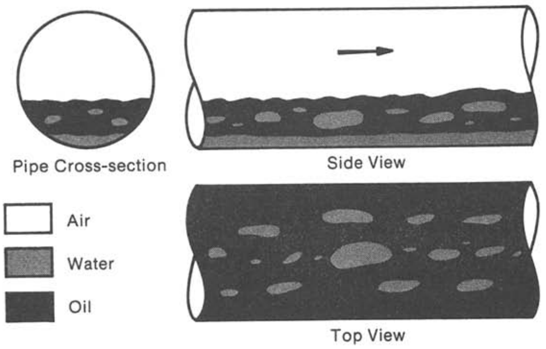

Figure 8. Schematic diagram of oil-based dispersed stratified/wavy flow (region 3).

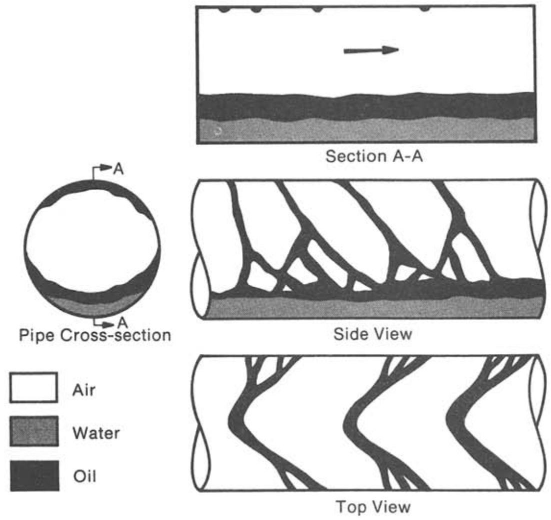

Figure 9. Schematic diagram of oil-based separated stratified/wavy flow (region 4).

Oil-based dispersed stratified/wavy flow

In this flow regime, stratification and gravitational phase separation was observed. As can be seen in the sketches shown in figure 8, on top of a continuous layer of water, there was an oil-based mixture having relatively large water droplets in it. In this region of the three-phase flow regime map, small-amplitude surface waves were observed on the oil/water layer.

Oil-based separated stratified/wavy flow

As can be seen in figure 9, for this flow regime the oil and water phases were completely separated. Due to gravitational stratification, the oil phase flowed on top of the water phase, and has a complicated wave structure that appeared on the top of the pipe. Ripple waves were also observed on the interface between the oil and water phases.

Oil-based separated wavy stratifying-annular flow

Figure 10 indicates that the upper oil structures observed in separated stratified/wavy flow became more dense in this flow regime and were connected with a thinner oil film, which caused

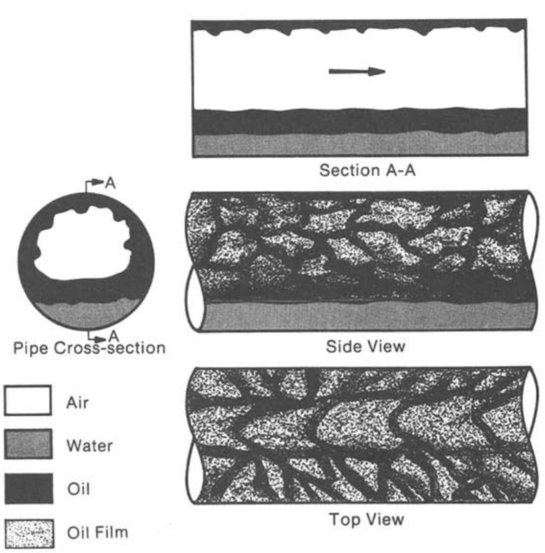

Figure 10. Schematic diagram of oil-based separated wavy stratifying-annular flow (region 5).

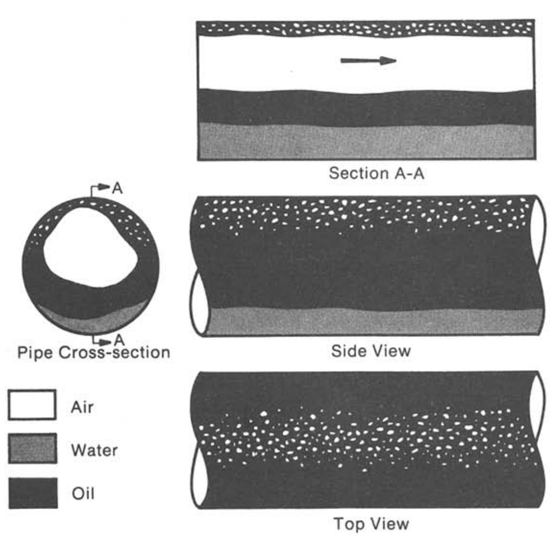

Figure 11. Schematic diagram of oil-based separated/dispersed stratifying-annular flow (region 6).

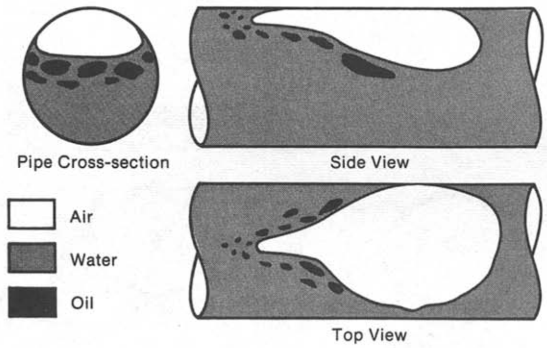

Figure 12. Schematic diagram of water-based dispersed slug flow (region 7).

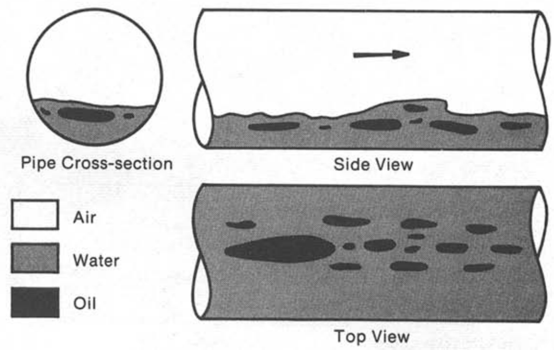

Figure 13. Schematic diagram of water-based dispersed stratified/wavy flow (region 8).

continuous wetting of the upper pipe wall. Interestingly, stratification still played a dominant role for this flow regime.

Separated/dispersed stratifying-annular flow

By increasing the air flow rate the variations in the oil film thickness on the upper pipe wall, which characterized the previous flow regime, disappeared. As can be seen in this flow regime (figure 11), small air bubbles in the oil film were observed towards the top of pipe. As in the previous flow regime, stratification effects were still evident.

Water-based dispersed slug flow

For relatively low air and high water flow rates, air bubbles having very distinct tails were observed. For this flow regime, the air phase was the driving phase. As can be seen in figure 12, a relatively high concentration of oil droplets in the regions following the air bubbles was observed.

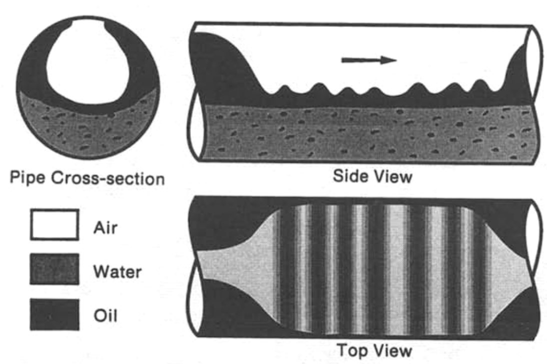

Figure 14. Schematic diagram of water-based separated dispersed incipient stratifying-annular flow (region 9).

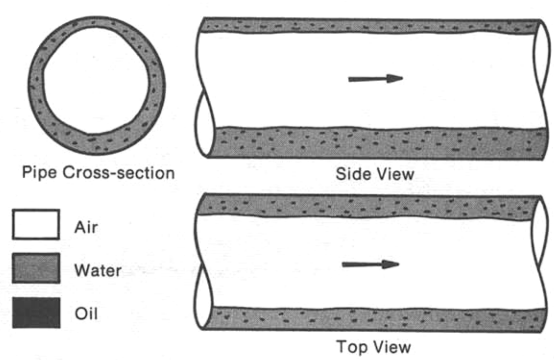

Figure 15. Schematic diagram of water-based dispersed stratifying-annular flow (region 10).

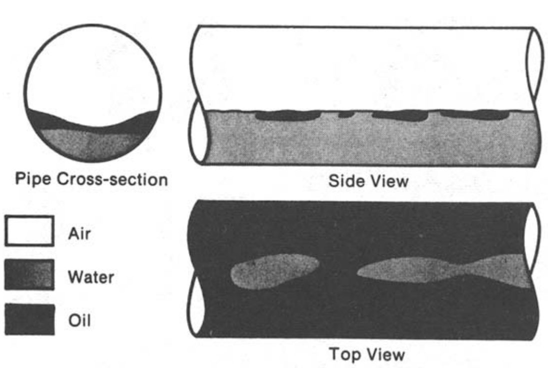

Figure 16. Schematic diagram of the boundary between water-based wavy flow and oil-based wavy flow.

On increasing the air flow rate the clear boundaries between the air plug tails and water phase were replaced by a frothy appearance at the back of the air plugs.

Water-based dispersed stratified/wavy flow

As can be seen in figure 13, this flow regime looked similar to a two-phase stratified/wavy flow with the exception of the dispersed oil droplets.

Water-based separated/dispersed incipient stratifying-annular flow

As the air flow is increased the relatively small waves shown in figure 13 are replaced by a new structure which includes roll waves. Moreover, liquid "phase" separation occurs, presumably due to graviational and shear effects. The resultant flow regime is shown in figure 14. It can be seen to be a rather complicated one, which is near a transition to stratifying-annular flow.

Water-based dispersed stratifying-annular flow

In this flow regime, which is shown schematically in figure 15, the pipe perimeter was wetted continuosuly by a water-based film which contained small oil droplets dispersed in it. The water film thickness differences between the top and the bottom of the pipe were most noticeable at lower superficial air velocities, and became smaller on increasing the air flow rate. Except for the dispersed oil droplets, this flow regime looked very much like two-phase stratifying-annular flow.

FLOW REGIME TRANSITION

As with two-phase flow, the transition boundaries in three-phase flows are very important regions of the flow regime map. However, unlike two-phase flows, in three-phase flows new transition boundaries exist at which there is a transition of the base fluid. Figure 16 shows one such boundary, at which the flow is close to transition from water-based stratified/wavy flow (figure 13) to oil-based dispersed stratified/wavy flow (figure 8).

Due to the many possible transport properties of three-phase fluid mixtures, the quantification of three-phase flow regime boundaries will be a challenging task. Nevertheless, the work presented herein hopefully makes a good first contribution to our understanding or horizontal three-phase flow regimes.

CONCLUSION

Three-phase flow for air/water/oil systems presents a rich variety of flow regimes. Particular flow regimes may or may not be desirable in different three-phase flow applications. Nevertheless, in order to obtain optimal design parameters and operating conditions, it is important to clearly understand three-phase flow regimes and the boundaries between them. The purpose of this paper has been to contribute to the knowledge base on three-phase flow regimes, and to motivate further investigations in this field.

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