POLSKA AKADEMIA NAUK

INSTYTUT MASZYN PRZEPŁYWOWYCH

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH

106

WYDAWNICTWO IMP PAN

GDAŃSK 2000

THE TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machines

*

PRACE INSTYTUTU MASZYN PRZEPŁYWOWYCH

poświęcone są publikacjom naukowym z zakresu teorii i badań doświadczalnych w dziedzinie mechaniki i termodynamiki przepływów, ze szczególnym uwzględnieniem problematyki maszyn przepływowych

Wydanie publikacji zostało dofinansowane przez PAN ze środków DOT uzyskanych z Komitetu Badań Naukowych

EDITORIAL OFFICE – REDAKCJA

Wydawnictwo Instytutu Maszyn Przepływowych
Polskiej Akademii Nauk
ul. Gen. Józefa Fiszera 14, 80-952 Gdańsk, skr. poczt. 621,
☎ (0-58) 341-12-71 wew. 141, fax: (0-58) 341-61-44,
e-mail: esli@imp.gda.pl

ISSN 0079-3205

TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 106, 2000, 3-12

JERZY HAPANOWICZ[1], LEON TRONIEWSKI[1] and STANISŁAW WITCZAK[1]

Flow of two immiscible liquids in horizontal pipes

The results of investigations in flow patterns of two-phase liquid-liquid flows in horizontal pipes with diameters of 12, 16 and 22 mm have been presented in the paper.

Water and two types of oil, i.e., machine oil, lighter than water, and tar oil, heavier than water, were investigated. As a result of conducted studies, the observed flow patterns were described, defined and named, moreover they were also systematized. The ranges of particular flow patterns have been presented in the form of flow pattern maps.

1. Introduction

Compared with the other two-phase systems, one can encounter several various relations of the physical properties of phases in the liquid-liquid system which is a mixture of two immiscible liquids. While considering only density and viscosity of components, one may distinguish mixtures in which one liquid, that constitutes the continuous phase, at the same time, will be a component of higher, equal or lower density or viscosity than the other one, i.e., the dispersed phase.

Some difficulties in the description of two-phase liquid-liquid mixture flow and also its rare occurrence, cause the experimental and theoretical studies on the subject to be still incomplete.

Investigations of the systems of two-phase liquid flow, as have been hitherto carried out, concentrated mainly on water-oil mixtures [1-5]. The density of oil, used in examinations, was less or equal to the density of water, whereas in industrial practice one can encounter flow of the two-phase liquid system where the more viscous phase is, at the same time, a component of higher density.

A detailed analysis together with a comparison of the results of our studies on the flow patterns in two-phase liquid-liquid flow are impossible to be presented

[1]Mechanical Department, Opole Technical University, S. Mikołajczyka 5, 45-233 Opole

here on account of the limited space of the present paper. However, one may state that up till now there has been a lack of generally-accepted uniform nomenclature of flow patterns. The authors of publications on the subject give different names to the observed flow patterns which makes both the comparison and utilization of the results of their studies difficult.

The ranges of the occurrence of the determined flow patterns and also the boundary lines between them are presented in the flow pattern maps, however, there is a lack of one universal map for the liquid-liquid system. This results from insufficient knowledge on the parameters directly affecting the formation of the determined patterns as well as from the absence of uniform names and definitions of particular patterns. Such a state of knowledge on the ranges of two-phase liquid-liquid flows has determined us to undertake our own studies [6].

2. Experimental investigations

The experimental investigations of two-phase liquid-liquid flow were conducted for two liquid system utilizing water and two types of oil. The former was the tar oil with the density of about 1200 kg/m^3 and with the viscosity of about 40mPa · s at the temperature of 20°C. The latter was the machine oil with the similar viscosity and density of 915 kg/m^3. The two-phase mixture, formed in a mixing chamber, flowed through a system of horizontal measuring glass channels with the diameters of 12, 16 and 22 mm and each was 1.5 m long and then was divided in a separator. The mixing chamber consisted of two pipes placed concentrically one in relation to the other. Oil flowed through the internal pipe (shorter one) whereas water flowed through the annular cross-section. Each of the measuring channels was equipped with the section stabilizing the flow of the length of 100 pipe diameters. The formation of two-phase flow patterns was observed in the light passing through pipe. Pictures of the channel section, which was 40 cm long, were taken. In additional, pressure drops were measured. The results of measurements of pressure drops will be discussed in another paper.

For the water-tar oil mixture, the range of variations in flow rates was as follows: $(0.5 \div 22.2) \cdot 10^{-5} m^3/s$ for water and $(3.9 \div 64.7) \cdot 10^{-6} m^3/s$ for oil. Such ranges of variations in flow rates corresponded to the alterations to the superficial velocity: $(0.013 \div 1.96)$m/s for water and $(0.01 \div 0.57)$m/s for oil. The oil fraction varied in the ranges from 1.7% to 93%. For the two-phase systems, water flow was both laminar and turbulent, whereas oil flow was only laminar. The laminar oil flow resulted, in the main, from its high viscosity. The temperature of the system was $20° \pm 2°$C.

Such ranges of flow rates permitted investigations to be carried out in the following four cases:

- the continuous phase is characterized by higher density and viscosity than the dispersed one,
- the continuous phase shows lower density and viscosity than the dispersed one,

- the continuous phase indicates higher density and lower viscosity than the dispersed one,
- the continuous phase reveals lower density and higher viscosity than the dispersed one.

3. Results of studies and their analysis

On the basis of observations of the variations occurring in two-phase liquid--liquid mixture flowing through the installation, some specific flow patterns, formed by particular phases, were distinguished, depending, in the main, on their flow velocities and fractions.

3.1. Water-tar oil flow

In water-tar oil mixture flow eight flow patterns were distinguished. They are presented in Fig. 1. Their detailed description is given bellow:

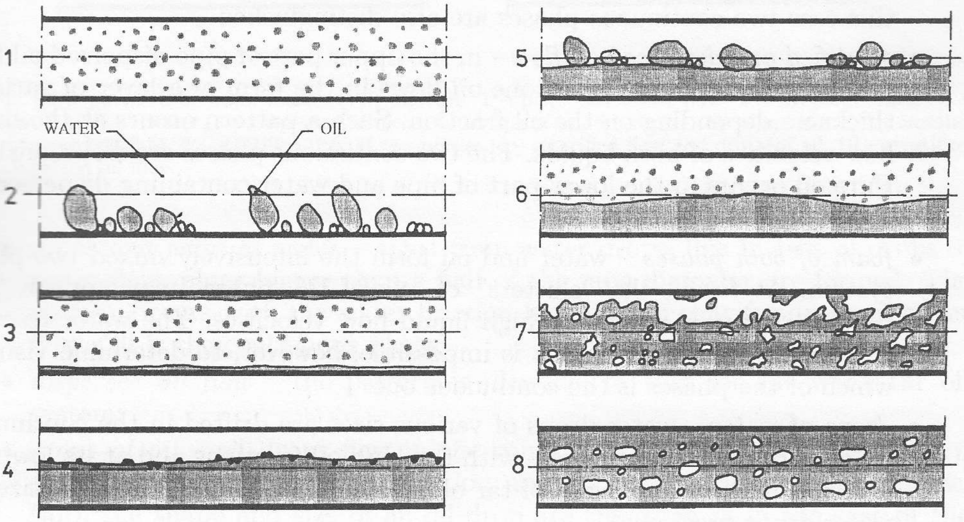


Fig. 1. Flow patterns of water-tar oil mixture. 1 – dispersed oil flow, 2 – drops of oil, 3 – annular and dispersed oil flow, 4 – stratified flow of both phases, 5 – stratified flow and drops of oil, 6 – stratified and dispersed oil flow, 7 – foam of both phases, 8 – drops of water.

- *dispersed oil flow* – small particles of oil, flowing through the entire pipe cross-section, are drifted by water. This type of flow pattern occurs at high water velocities with low oil fractions. Water is the continuous phase.
- *drops of oil* – oil forms spherical particles of various sizes, however, they are not bigger than a half of the pipe diameter. The characteristic of the flow pattern is such that oil structures flow along the "bottom" of pipe.

The described pattern occurs at low flow velocities of both phases. Water constitutes the continuous phase.

- *annular and dispersed oil flow* – oil forms a film on the pipe walls and at the same time it flows as a dispersed form in the water stream. The pattern occurs at the highest flow velocities of both phases. Water is the continuous phase. It is probable (but not proved in investigations) that wettability of the pipe material (glass) by oil has significant effect on the formation of this pattern.
- *stratified flow of both phases* – oil and water flow independently of each other forming layers in the upper and lower parts of pipe. Their thickness varies according to the phase fractions. The pattern occurs at the mean flow velocities of both components. Water is the continuous phase in the upper part of the pipe whereas oil in the lower one.
- *stratified flow and drops of oil* – on the surface of the layer of oil, flowing along the "bottom" of channel, oil drops are formed which are at times washed away by water. The pattern was observed at higher flow velocities than those for the typically stratified flow and with the similar phase fraction. In this case two continuous phases are also distinguished.
- *stratified and dispersed oil flow* – in the upper part of pipe dispersed oil flow occurs whereas in the lower one oil flows in the form of a layer of variable thickness depending on the oil fraction. Such a pattern occurs at the mean flow velocities of both liquids. The two continuous phases are distinguished. Pure oil occurs in the lower part of pipe and water containing dispersed oil occurs in the upper one.
- *foam of both phases* – water and oil form the intensively mixed two-phase system. At times, the "clusters" of one of the phases may appear. The pattern occurs at relatively high liquid flow velocities. The water fraction is higher than the oil one. It is impossible, however, to determine visually which of the phases is the continuous one.
- *drops of water* – water drops of various sizes are drifted in the continuous oil phase. The pattern occurs with the high oil fractions and at its low flow velocity. In view of opacity of tar oil it is difficult to determine the sizes of water drops precisely.

3.2. Water-machine oil flow

On the basis of observations of variations occurring in the water-machine oil flow, as many as 10 flow patterns were distinguished. There are presented in Fig. 2. Their names and detailed description are as follows:

- *dispersed water flow* – the pattern is identical to dispersed oil flow. Oil constitutes the continuous phase;
- *drops of water* – water drops of various sizes flow in the continuous oil phase. Oil is the continuous phase;

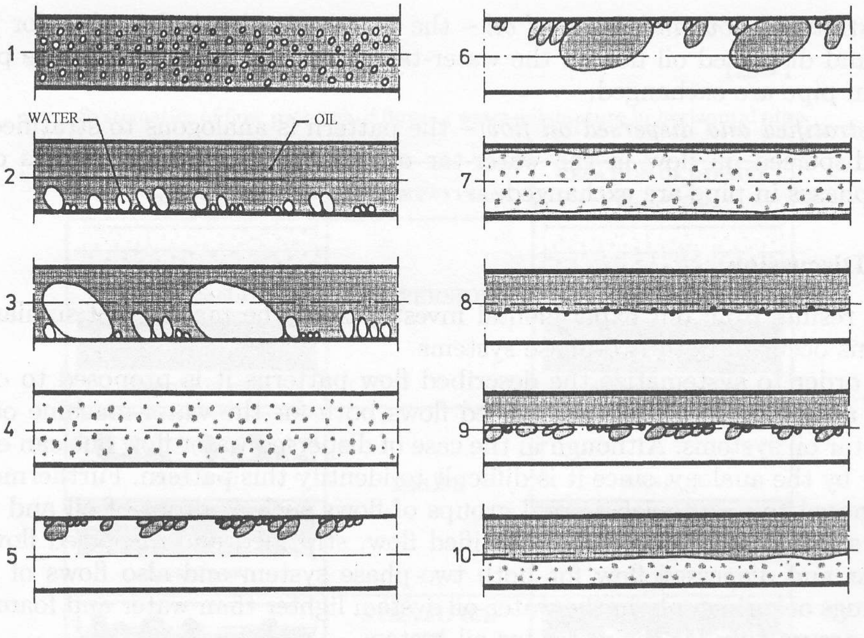


Fig. 2. Flow patterns of water-machine oil mixture. 1 – dispersed water flow, 2 – drops of water, 3 – drops and plugs of water, 4 – dispersed oil flow, 5 – drops of oil, 6 – drops and plugs of oil, 7 – annular and dispersed oil flow, 8 – stratified flow of two phases, 9 – stratified flow and drops of oil, 10 – stratified and dispersed oil flow.

- *drops and plugs of water* – apart from water drops, like in case of drops of water flow, plugs bigger than a half of the pipe diameter are formed. The pattern occurs with the water fraction higher than that for drops of water flow. Oil is the continuous phase;
- *dispersed oil flow* – the pattern is identical to that for the water-tar oil system;
- *drops of oil* – oil drops flow in the continuous water phase. The pattern occurs with the high water fraction and at low velocities of the phases. Both the shape and size of an oil drop are the same as in the case of the water-tar oil mixture;
- *drops and plugs of oil* – the pattern is analogous to that for water drops and plugs of water flow, however, with the exchanged "roles" of both phases;
- *annular and dispersed oil flow* – the pattern is identical to that for the water-tar oil system;
- *stratified flow of two phases* – oil and water flow independently of each other forming layers in the upper and lower parts of pipe. The pattern is identical to that for the water-tar oil mixture. However, locations of the phases in pipe are exchanged;

- *stratified flow and drops of oil* – the pattern is identical to that for drops and dispersed oil flow in the water-tar oil system. Locations of the phases in pipe are exchanged;
- *stratified and dispersed oil flow* – the pattern is analogous to stratified and dispersed oil flow in the water-tar oil system. Only the locations of the phases in pipe are exchanged.

3.3. Discussion

As results from our experimental investigations the majority of similar flow patterns occur in both two-phase systems.

In order to systematize the described flow patterns it is proposed to distinguish, according to Table 1, dispersed flows both for the water-machine oil and water-tar oil systems. Although in the case of dispersed water flow one can expect it only by the analogy, since it is difficult to identify this pattern. Furthermore, it is proposed to distinguish several groups of flows such as drops of oil and water flows, stratified and drop flow, stratified flow, stratified and dispersed flow and annular and dispersed flow for both two-phase system and also flows of drops and plugs occuring only in the water-oil system lighter than water and foam flow, which occurs only for the water-tar oil system.

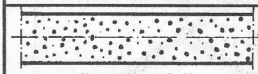
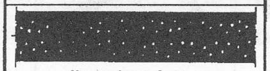
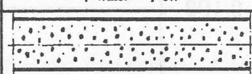
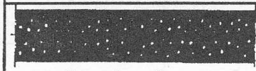
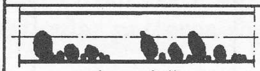
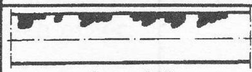
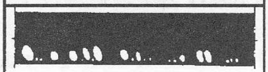
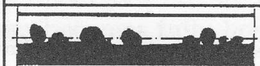
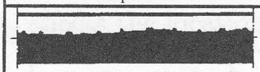
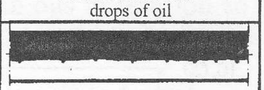
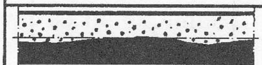
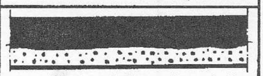
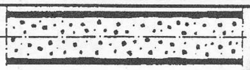
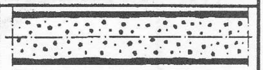
A lack of equivalents of some flow patterns in both two-phase systems results only from the fact that they were not observed during our investigations. However, in the generalized systematization of flow patterns for the liquid-liquid systems one should assume the possibility of occurrence of all proposed and all known flow patterns in the two-phase mixture.

The ranges of occurrence of particular flow patterns are presented in flow pattern maps. In view of the fact that the patterns, observed during our studies of both two-phase systems, differ in their number and in the range of their occurrence, after many trials a decision was made to draw two independent flow pattern maps for these two cases. For both mixtures, the ranges of particular patterns were plotted depending on the ratio of superficial velocities of oil to water, which was presented by the horizontal axis. On the other hand, the vertical axis represented the superficial velocity of water (it includes the influence of the channel diameter). Figs 3 and 4 present flow pattern maps for both two-phase systems. As results from them, flow with small oil particles occurs with small fractions of that phase and at high water flow velocities. Analogously, dispersed water flow occurs with the low water fraction in relation to oil which constitutes the continuous phase. These two ranges are seperated by the area of intermediate flow patterns.

Although, the presented flow pattern maps do not contain strict boundary lines, they may be instrumental in the estimation of the possible occurrence of given patterns in pipes with the diameters from the range $12 \div 22$ mm when only flow rates of the phases are known. An advantage of these maps is the fact that they are valid for a wide range of superficial velocities of both phases, component fractions and various relations of liquid densities.

Table 1

Systematics of flow patterns of flowing water-oil mixture in horizontal pipe

RELATION OF DENSITY $\rho_{water} < \rho_{oil}$	FLOW PATTERN	RELATION OF DENSITY $\rho_{water} > \rho_{oil}$
 dispersion of oil  dispersion of water	**DISPERSION**	 dispersion of oil  dispersion of water
 drops of oil  drops of water	**DROPS**	 drops of oil  drops of water
 stratified flow with drops of oil	**STRATIFIED and DROPS**	 stratified flow with drops of oil
 stratified flow of both phases	**STRATIFIED**	 stratified flow of both phases
 stratified and dispersion of oil	**STRATIFIED and DISPERSION**	 stratified and dispersion of oil
 annular and dispersion of oil	**ANNULAR and DISPERSION**	 annular and dispersion of oil
not observed	**DROPS and PLUGS**	 drops and plugs of oil  drops and plugs of water
 foam of water and oil	**FOAM**	not observed

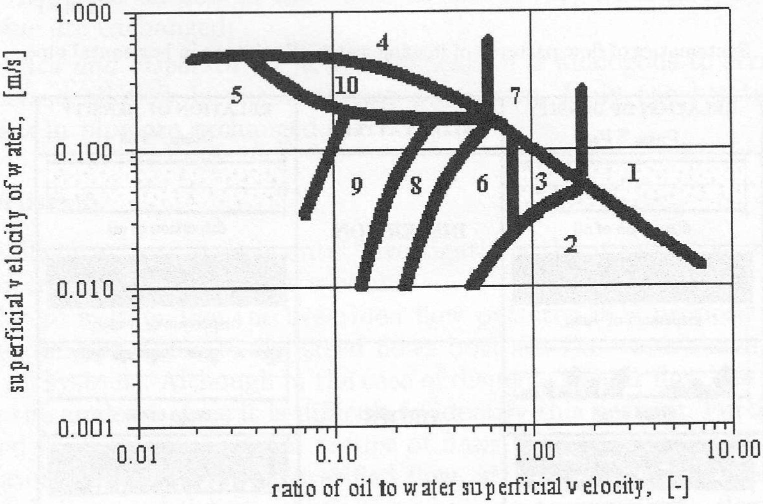


Fig. 3. Flow pattern map for water-tar oil mixture. Numbers of flow patterns according to Fig. 1.

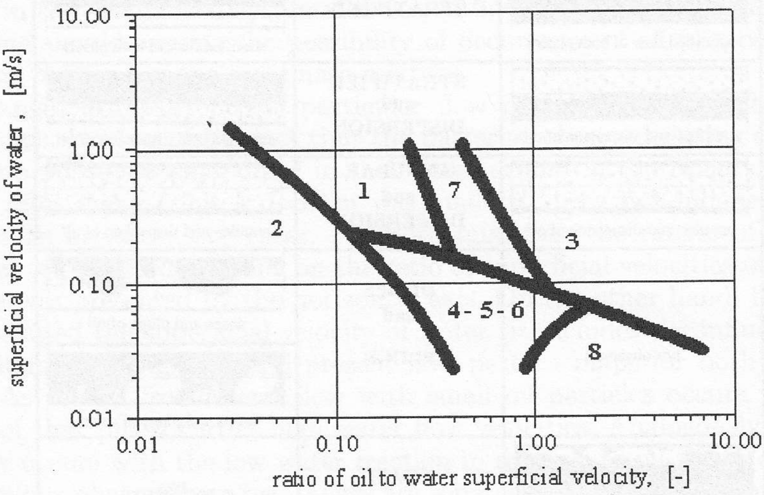


Fig. 4. Flow pattern map for water-machine oil mixture. Numbers of flow patterns according to Fig. 2.

4. Conclusions

As a result of the analysis of the collected experimental material, it is possible to draw some general conclusions, namely:

- the majority of the observed flow patterns occur in both two-phase systems irrespective of the ratio of phase density;
- in general, one can distinguish 8 groups of flow patterns (according to our studies), however, flows of drops and plugs occur only in the water-machine oil system and flow of foam exists only in the water-tar oil mixture;
- as results from the analysis of flow pattern maps, the ranges of occurrence of particular patterns slightly differ with each other;
- the dispersed phase tends to form drops and plugs of big sizes together with the decrease in the velocity of flow (with the increase in the channel diameter). When the flow velocity of the continuous phase increases the dispersed phase undergoes further dispersion. With the adequate phase fractions, the system becomes fully homogeneous;
- the difference in the ratio of density of both oils in relation to water, in the main, affects the location of the phases in the channel;
- the reason why all the flow patterns do not occur in both two-phase systems has yet to be explained.

Received 20 July 1999

References

[1] Charles M. E., Govier G. W., Hodgson G. W.: *The horizontal pipeline flow of equal density oil-water mixture*, Can. J. Chem. Eng., 39(1961), 27-36.

[2] Martinez A. E., Arirachakaran S., Shoham O., Brill J. P.: *An analysis of oil-water flow phenomena in horizontal pipes*, SPE Proc. Prod. Operation Symp., SPE 18836(1989), 155-167.

[3] Brauner N., Moalem Maron D.: *Flow pattern transistions in two phase liquid-liquid flow*, Int. J. Multiphase Flow, 18(1992), No. 1, 123-140.

[4] Fujii T., Ohta J., Takenaka N., Morimoto O., Nakazawa T.: *The flow characteristics of a horizontal immiscible equal-density-liquids two phase flow*, Proc. of the Int. Conf. on *Multiphase Flows'91* – Tsukuba (1991), 195-198.

[5] Mukheriee H., Brill J.P., Beggs H.D.: *Experimental study of oil-water flow in inclined pipes*, Trans. of ASME, 103(1981), 56-66.

[6] Hapanowicz J.: *Two-phase liquid-liquid flow in horizontal pipes*, Ph.D. Thesis, Polish Academy of Sciences, Institute of Chemical Engineering in Gliwice (1996).

Przepływ dwóch nie mieszających się cieczy w rurach poziomych

Streszczenie

W pracy przedstawiono wyniki badań dotyczących struktur przepływu dwufazowego dwóch nie mieszajacych się wzajemnie cieczy. Badania prowadzono w poziomych szklanych rurach o średnicy 12, 16 i 22 mm, wykorzystując jako czynniki robocze wodę i dwa rodzaje olejów: olej maszynowy – lżejszy od wody olej smołowy – cięższy od wody. Lepkość obu olejów była do siebie zbliżona. Rezultatem prac było zidentyfikowanie, nazwanie i zdefiniowanie obserwowanych struktur przepływu, a także podanie ich systematyki. W celu określenia zakresów występowania poszczególnych struktur, zaproponowano dwie odrębne mapy przepływu.