Pergamon

Int. J. Multiphase Flow Vol. 23, No. 1, pp. 55–68, 1997
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0301-9322/97 $17.00 + 0.00

PII: S0301-9322(96)00055-9

FLOW INDUCED EMULSIFICATION IN THE FLOW OF TWO IMMISCIBLE LIQUIDS IN HORIZONTAL PIPES

M. NÄDLER and D. MEWES
Institut für Verfahrenstechnik, Callinstrasse 36, D-30167 Hannover, Germany

(Received 29 September 1994; in revised form 30 July 1996)

Abstract—The flow of two immiscible liquids in a horizontal pipe with an inner diameter of 59 mm and a total length of 48 m is experimentally investigated. Results are presented for the effect of emulsification and phase inversion on the pressure drop for different flow regimes of two phase oil–water mixtures. The measurements are conducted for oil viscosities of 22, 27 and 35 mPas, which are obtained by changing the temperature of the liquids. For the flow conditions investigated maximum pressure drops are measured in the region of phase inversion which is observed for input water fractions between 10 and 20%. There is no significant effect of the temperature on the flow characteristics observed. Copyright © 1996 Elsevier Science Ltd.

Key Words: phase inversion, immiscible liquids, oil-water mixtures, flow regimes, emulsions, pressure drop, drag reduction

1. INTRODUCTION

In pipelines for oil production, mixtures of oil and water are transported over long distances. By increasing the production period of wells, the amount of water in the well stream increases resulting in water concentrations up to 98% by volume. For transporting heavy viscous crude oil, water is introduced in controlled amounts into the pipeline in order to reduce the pressure gradient along the pipeline and hence the pumping power required to transport the oil through the pipelines. The greatest reduction in the pressure drop is expected when water, which is the less viscous liquid phase, forms a uniform annulus along the pipe wall, while the more viscous oil phase flows within the annulus (Charles 1960; Charles *et al.* 1961; Hasson *et al.* 1979; Oliemans *et al.* 1986, 1987; Arney *et al.* 1993).

The results of investigations of the two phase flow of immiscible liquids in horizontal pipes (Russell *et al.* 1959; Charles *et al.* 1961; Guzhov *et al.* 1973; Arirachakaran *et al.* 1989; Hall 1992; Brauner and Moalem Maron 1992; Fujii *et al.* 1994) indicate that the pressure drop of the pipeline flow of two immiscible liquids strongly depends on the flow regime and hence the distribution of the two liquids in the cross-sectional area of the pipe. The turbulent mixing taking place in the pipeline can be sufficient to disperse the initially separated phases, so that dispersions and emulsions are formed resulting in higher pressure drops (Russell *et al.* 1959). For oil-in-water emulsions consisting of oil droplets dispersed in a continuous water phase, a reduction in the pressure drop is possible (e.g. Sanchez and Zakin 1994), while in the case of water-in-oil emulsions the pressure drop can be significantly higher than the pressure drop for the pure oil alone flowing in the pipeline (Rose and Marsden 1970). The flow behaviour of emulsions of oil and water depends on the volume fraction and the droplet distribution of the dispersed phase (Pilehvari *et al.* 1988). As shown in several studies (e.g. Mao and Marsden 1977; Zakin *et al.* 1979; Pal 1987, 1993) emulsions with volume fractions of the dispersed phase higher than 0.5 often behave as non-Newtonian shear thinning fluids. Furthermore, the results of these studies indicate that the degree of drag reduction of the emulsions increases with an increase in the volume fraction of the dispersed phase. In case of unstable emulsions the degree of drag reduction of water-in-oil emulsions is found to be higher than in the case of oil-in-water emulsions (Pal 1993).

An abrupt increase in the pressure drop to values of an order of magnitude higher than the pressure drop of the pure oil is observed in the region of phase inversion, where the external phase inverts from water to oil or vice versa. The occurence of phase inversion in mixtures of oil and

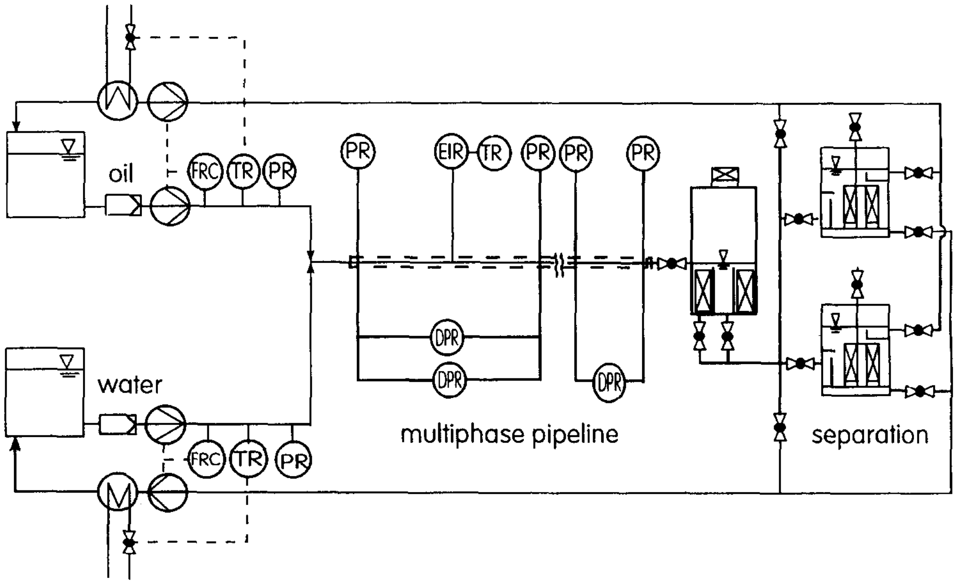

Figure 1. Experimental setup.

water depends on the water volume fraction $\epsilon_{f1} = V_{f1}/V_{f1} + V_{f2}$ and the input water volume fraction $\dot{\epsilon}_{f1} = \dot{V}_{f1}/\dot{V}_{f1} + \dot{V}_{f2}$, respectively, where V is the volume and $\dot{V}$ is the volumetric flow rate of the phases. The water and the oil are denoted with the index f1 and f2, respectively. In the case of equal size drops and rhombohedral packing the volume fraction of the dispersed phase is limited to 74%. As shown in several studies on oil-in-water emulsion (e.g. Pal *et al.* 1986; Pilehvari *et al.* 1988; Plegue *et al.* 1989) the maximum volume fraction of the dispersed phase can be up to 90%. This high dispersed phase fraction are possible by oil droplets which are polyhedral in shape and separated by thin interfacial aqueous films and by multiple emulsion characterized by water-in-oil-in-water drops or vice versa. By increasing the volume fraction of the dispersed phase above the maximum concentration the emulsion becomes unstable and phase inversion occurs. The water volume fraction at the inversion point $\epsilon_{f1,I}$ decreases by increasing the oil viscosity η_{f2} and hence an increasing viscosity ratio $\eta_f^* = \eta_{f2}/\eta_{f1}$. (Yeh 1964; Arirachakaran *et al.* 1989; Efthimiadu and Moore 1994; Brooks and Richmond 1994). In investigations of agitated oil–water dispersions

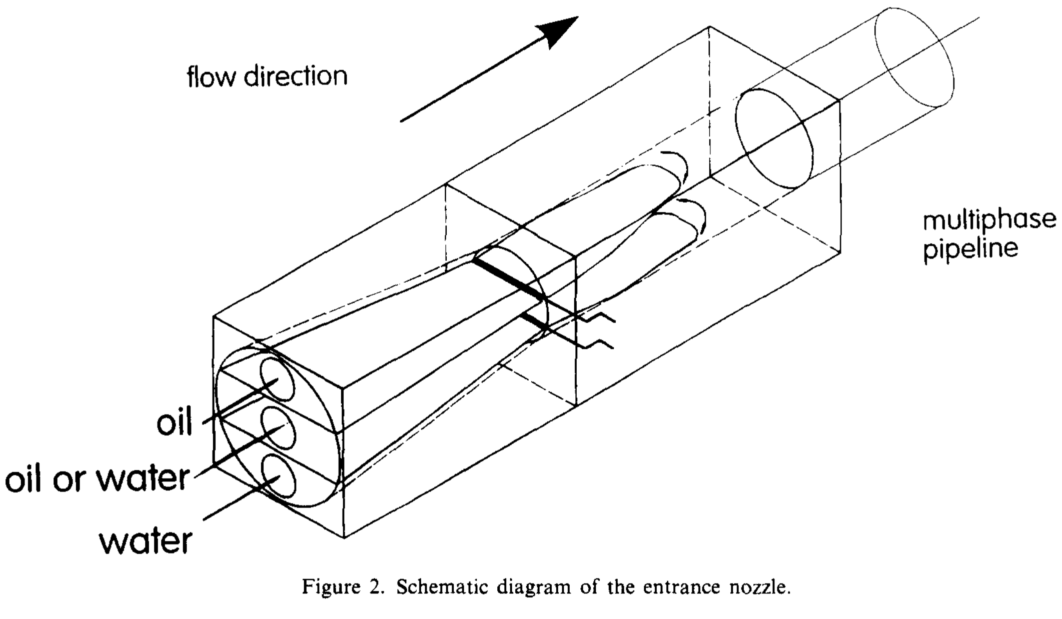

Figure 2. Schematic diagram of the entrance nozzle.

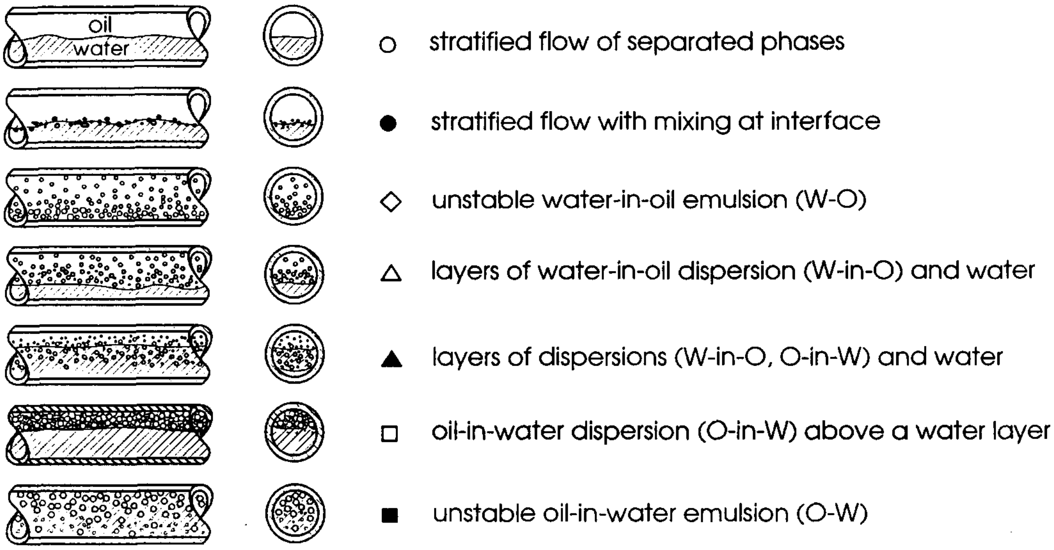

Figure 3. Schematic diagram of flow regimes of the two-phase flow of water and oil.

(Brooks and Richmond 1994) it is found that increasing the oil viscosity leads to larger amounts of the oil phase emulsified within the water phase and hence a reduction of the inversion water fraction $\epsilon_{\mathrm{f1,I}}$, where for oil viscosities above $\eta_{\mathrm{f2}} \approx 0.2$ Pas a constant value of $\epsilon_{\mathrm{f1,I}} = 0.15$ is observed.

Furthermore, the phase inversion is influenced by the shear rate and hence by the mixture velocity $j_{\mathrm{f}} = (\dot{V}_{\mathrm{f1}} + \dot{V}_{\mathrm{f2}})/A$ which is defined as the sum of the volumetric flow rates of the water phase and the oil phase, related to the pipe cross sectional area $A = \pi/4\, d^2$ (Rose and Marsden 1970; Guzhov *et al.* 1973).

In this paper the flow of oil and water in a horizontal pipe is experimentally investigated in order to determine the effect of input water fraction, mixture velocity and viscosity ratio on emulsification and phase inversion.

2. EXPERIMENTAL SETUP

The experimental investigations are conducted in the experimental setup shown in figure 1. Water and oil used as the liquid phases are conveyed from separate supply vessels into the pipeline. The oil being used is a nonconductive, mineral white oil (Shell Ondina 17). The pure oil exhibits Newtonian flow characteristics while emulsions of the oil can show non-Newtonian flow behaviour as shown in a previous work (Nädler and Mewes 1995a). The volumetric flow rates of the liquids are regulated by varying the number of revolutions of the centrifugal pumps. The volumetric flow rates of all phases can be regulated independently and are measured by turbine flow meters and orifice gauges. In the experiments the superficial liquid velocity is varied in the range from $j_{\mathrm{f}} = 0.1$ to $j_{\mathrm{f}} = 1.6$ m/s.

The viscosities of the liquids are varied by changing the temperature of the liquid phases in the range from 18 to 30°C by means of heat exchangers. For this range of temperature the corresponding range of oil viscosity is from $\eta_{\mathrm{f2}} = 35$ mPas to $\eta_{\mathrm{f2}} = 22$ mPas and the range of the viscosity ratio $\eta_{\mathrm{f}}^* = \eta_{\mathrm{f2}}/\eta_{\mathrm{f1}}$ is from $\eta_{\mathrm{f}}^* \approx 35$ to $\eta_{\mathrm{f}}^* \approx 28$, respectively. The change of the density ratio $\varrho^* = \varrho_{\mathrm{f2}}/\varrho_{\mathrm{f1}}$ is less than 1% so that effects on the mixing of oil and water due to the change of the density ratio seem to be negligible in comparison to the changes in the viscosity ratio in the order of 25%.

The pure phases of oil and water are fed into the pipeline by a nozzle which is shown in figure 2. The nozzle is cone-shaped. It has three sections separated by baffle plates. Each baffle plate consists of two parts, the second of which can be inclined upwards and downwards. This design has been selected to prevent the formation of emulsions due to mixing effects taking place in the entrance nozzle. The phases are fed into the pipeline in layers corresponding to their densities resulting in a stratified flow regime just behind the nozzle. In contrast to feeding an emulsion into the pipeline the emulsions investigated in this study are formed from initially separated layers of oil and water and are of unstable nature.

The multiphase flow pipeline is manufactured of perspex tubing with an internal diameter of $d = 59$ mm. The total length of this pipeline between the entrance nozzle and the separation unit is approximately 48 m. The pipeline consists of two horizontal legs with a leg length of 25 and 23 m, respectively, connected by a horizontal U-bend. The measurements of the pressure drop in the first leg are taken behind an entrance length l_e of approximately 13 m ($l_e/d \approx 225$) downstream from the entrance nozzle. The measurements in the second leg are taken behind a length of approximately 15 m between the bend and the upstream pressure taping ($l_e/d \approx 680$ from the entrance nozzle).

It has been confirmed in the experimental investigation that the effect of the U-bend on the flow characteristics is only weak. Nevertheless, in the experimental investigations differences in the flow characteristics are determined between the first and the second leg. So the size of the droplets dispersed decreases significantly while the mixture flows downstream. By increasing distance from the entrance nozzle and hence a longer mixing period a smaller mean diameter of the droplets is

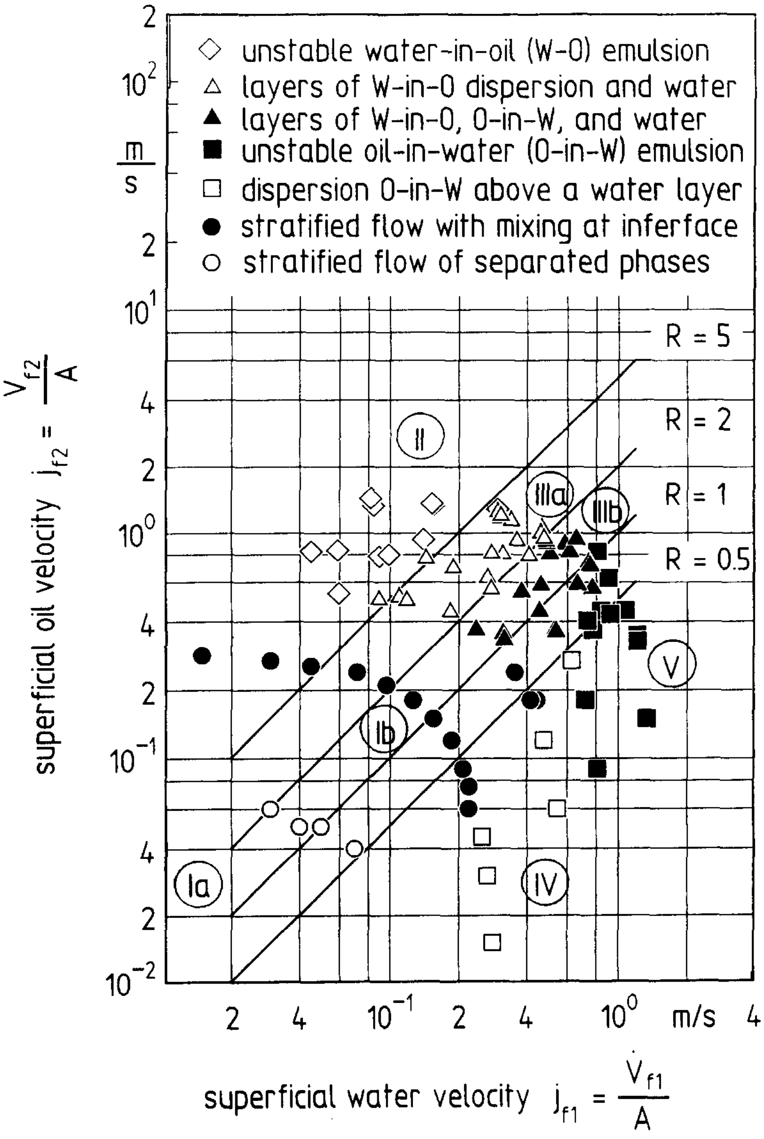

Figure 4. Flow regime map based on superficial velocities for the two-phase flow of water and oil.

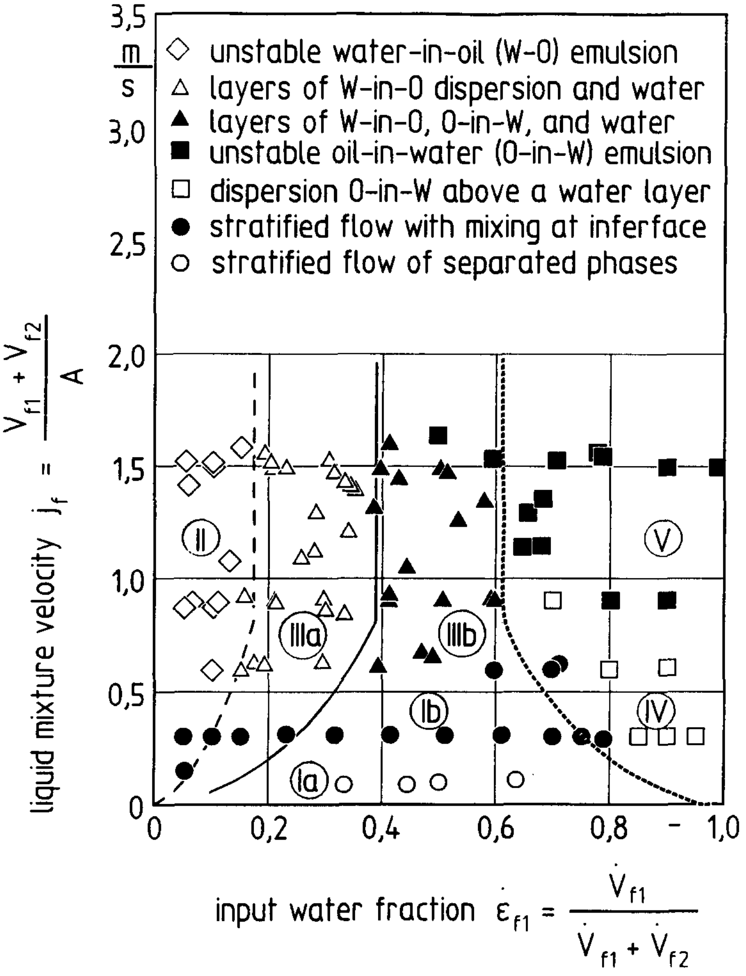

Figure 5. Flow regime map based on input water fraction for the two-phase flow of water and oil (- -calculated by [1], $k_1 = 3$, $k_2 = 1.2$ —calculated by [1], $k_1 = 1$, $k_2 = 1.2$ and ----calculated by [1], $k_1 = 1$, $k_2 = -1.2$).

observed at a given liquid mixture velocity and hence a given intensity of mixing. Furthermore, by increasing the liquid mixture velocity and hence the intensity of mixing for a constant distance from the entrance nozzle (e.g. $l_e/d = 225$ and $l_e/d = 680$) the size of the droplets decreases. These observations agree with the results obtained in experiments reported by Pilehvari *et al.* (1988).

In the first leg the decrease of the size of the droplets of the dispersed phase with increasing entrance length agrees with the results reported by Collins and Knudsen (1970). In the second leg the droplet size seems to be nearly constant. This supports the assumption of Karabelas (1978) that a maximum stable drop diameter is formed behind an entrance length of 600 times the internal pipe diameter.

3. FLOW REGIMES OF THE TWO PHASE FLOW OF OIL AND WATER

The flow regimes observed in the multiphase pipeline are shown schematically in figure 3. The flow regimes are compared using the flow regime maps given in figures 4 and 5. The flow is identified as a dispersion if in the cross-sectional area of the pipe there are layers consisting of a continuous phase in which the other phase is nonuniformly dispersed as well as layers of the pure liquids. For emulsions, one continuous phase is flowing in the entire pipe cross-sectional area, while the other phase is dispersed in the whole cross-sectional area of the pipe in nearly equally sized droplets within the continuous phase.

In order to detect the type of the emulsion formed in the pipeline and the occurrence of phase inversion the electrical conductance of the flowing mixture is measured by means of an in-line conductance cell. Phase inversion and emulsification is identified by changes in the conductance of the oil–water mixture.

In the present study, phase inversion is observed in the flow regime of layers of oil-in-water and water-in-oil dispersion and a pure water layer which is flowing above the bottom of the pipe (region III in figure 3). The results of the present investigation indicate that phase inversion takes place within the dispersion layer and hence only in a restricted part of the cross-sectional area of the pipe.

By contrast "emulsification" takes place within the whole pipe cross-sectional area and results in only one continuous liquid phase flowing in the pipeline while the second liquid phase, fully dispersed within the continuous phase, is flowing as droplets within the whole pipe cross-sectional area (region II and V in figure 3). Therefore, in the present study it is distinguished between the flow conditions for phase inversion within the dispersion layers and the conditions required for the formation of oil-in-water and water-in-oil emulsions, respectively.

The formation and the type of emulsions formed from two pure immiscible liquids is influenced by the wetting properties of the equipment used for the investigations (eg. Joseph *et al.* 1984b; Efthimiadu and Moore 1994). As in the present study a perspex pipe is used, a wetting of the pipe wall by the oil phase is favoured. Otherwise, according to the "viscous dissipation" principle, which postulates that the amount of viscous dissipation is minimized for a given flow rate, the flow of

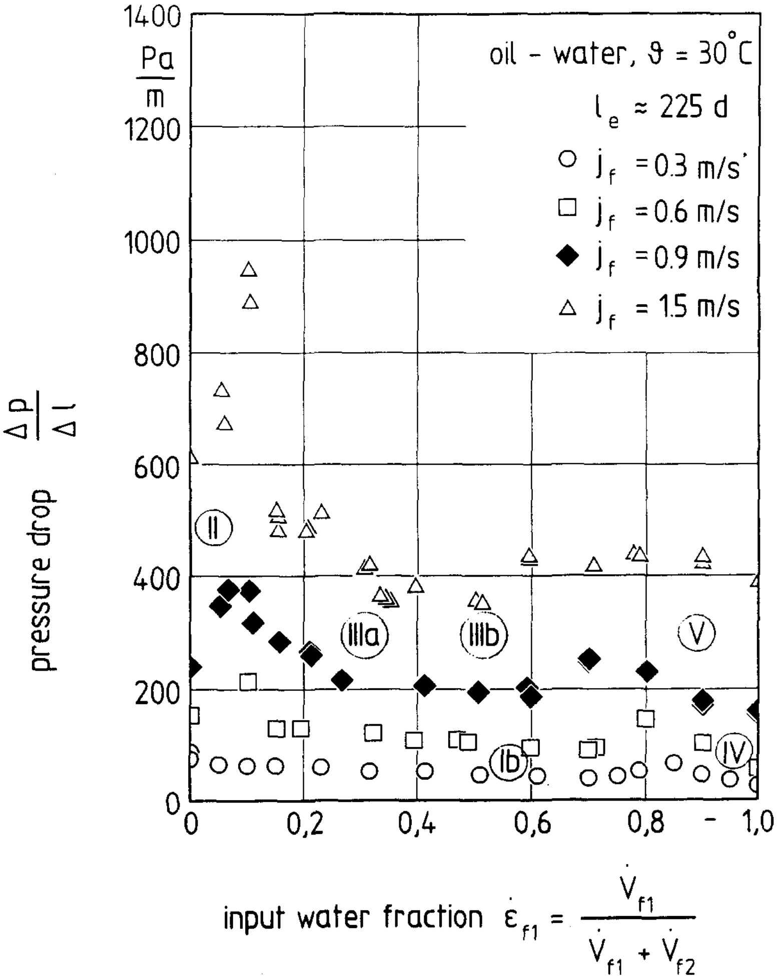

Figure 6. Pressure drop of the two-phase flow of water and oil for a liquid viscosity ratio of $\eta^* = \eta_{f2}/\eta_{f1} = 28$ ($l_e/d \approx 225$).

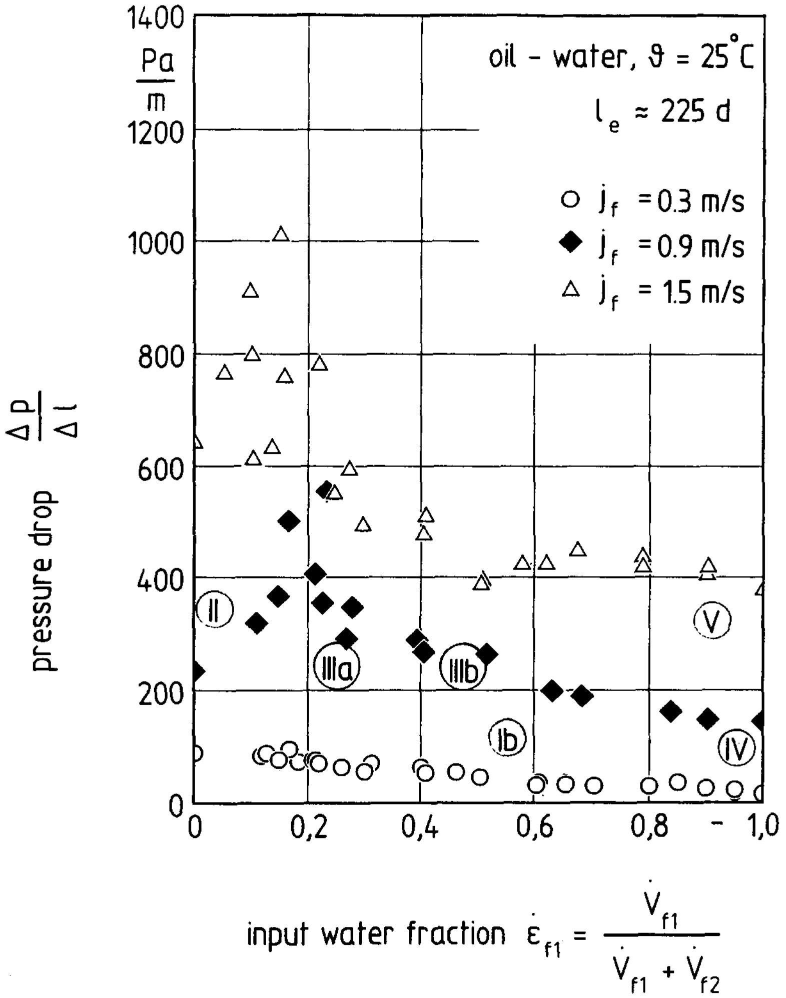

Figure 7. Pressure drop of the two-phase flow of water and oil for a liquid viscosity ratio of $\eta^* = \eta_{f2}/\eta_{f1} = 30$ ($l_e/d \approx 225$).

the less viscous water phase at the pipe wall is favoured (Joseph *et al.* 1984a, b). Furthermore, the liquid phase wetting the pipe wall is effected by the densities of the liquids. The lower density of the oil phase used in the present study supports a wetting of the pipe wall in upper pipe cross-sectional area by the oil phase while above the bottom of the pipe the wall is wetted by the water phase.

In figure 4 the flow regimes observed in the pipeline are shown in a diagram of the superficial velocities of the oil and the water phase. In this figure the solid lines represent a constant oil–water ratio $R = \dot{V}_{f2}/\dot{V}_{f1} = 1/\dot{\epsilon}_{f1} - 1$, which is $R = 0$ in the case of water flowing alone in the pipe and $R = \infty$ in the case of oil flowing alone.

In the range of low superficial oil and water velocities the stratified flow regime is observed (region I in figure 4). In the case of oil–water ratios less than $R = \frac{1}{3}$ the oil is flowing under the top of the pipe dispersed in droplets within the water phase (IV).

Increasing the velocities of both phases results in increasing turbulence in the flow and the formation of dispersions (III). The region of dispersions (III) seems to be limited by the lines for oil–water ratios of $R = 1$ and $R = 5$. This region corresponds to input water fractions between $\dot{\epsilon}_{f1}\{R = 5\} = 0.17$ and $\dot{\epsilon}_{f1}\{R = 1\} = 0.5$.

According to the experimental results phase inversion takes place for an oil–water ratio in the order of $R \approx 2$ corresponding an input water fraction of $\dot{\epsilon}_{f1}\{R = 2\} = 0.33$.

For oil–water ratios above $R = 5$ the water becomes totally dispersed within a continuous oil phase, so that water-in-oil emulsions are formed (region II). In contrast, the formation of oil-in-water emulsions (region V) does not seem to be significantly effected by the oil–water ratio. The results shown in figure 4 indicate that there is a critical superficial water velocity in the order of $j_{f1} \approx 0.6$ m/s which is required for the onset of emulsification and the formation of unstable oil-in-water emulsions (region V). In the turbulent flow regime, the coalescence within these emulsions seems to be negligible.

In figure 5 the flow regimes distinguished in the present study are shown in a plot of the liquid mixture velocity j_f vs the input water fraction $\dot{\epsilon}_{f1}$ as proposed by Guzhov *et al.* (1973).

The lines shown in figure 5 are predicted by an equation

$$\dot{\epsilon}_{f1,l} = \frac{1}{1 + k_1\left(\frac{C_{f2}}{C_{f1}}\,\frac{\varrho_{f2}^{(1-n_{f2})}}{\varrho_{f1}^{(1-n_{f1})}}\,\frac{\eta_{f2}^{n_{f2}}}{\eta_{f1}^{n_{f1}}}\,\frac{1}{[d j_f]^{(n_{f2}-n_{f1})}}\right)^{1/k_2}}$$

proposed in a previous work (Nädler and Mewes 1995b).

In this equation ϱ_{f1} and ϱ_{f2} are the densities and η_{f1} and η_{f2} are the viscosities of the pure phases of water and oil, respectively, C and n are parameters of the friction factor equation $C\ \mathrm{Re}^{-n}$ and k_1 and k_2 are empirical parameters. In order to predict whether the phases flow laminar or turbulent the superficial Reynolds numbers $\mathrm{Re}_{f1} = j_f d \rho_{f1}/\eta_{f1}$ and $\mathrm{Re}_{f2} = j_f d \rho_{f2}/\eta_{f2}$ are applied, respectively (Nädler and Mewes 1995b).

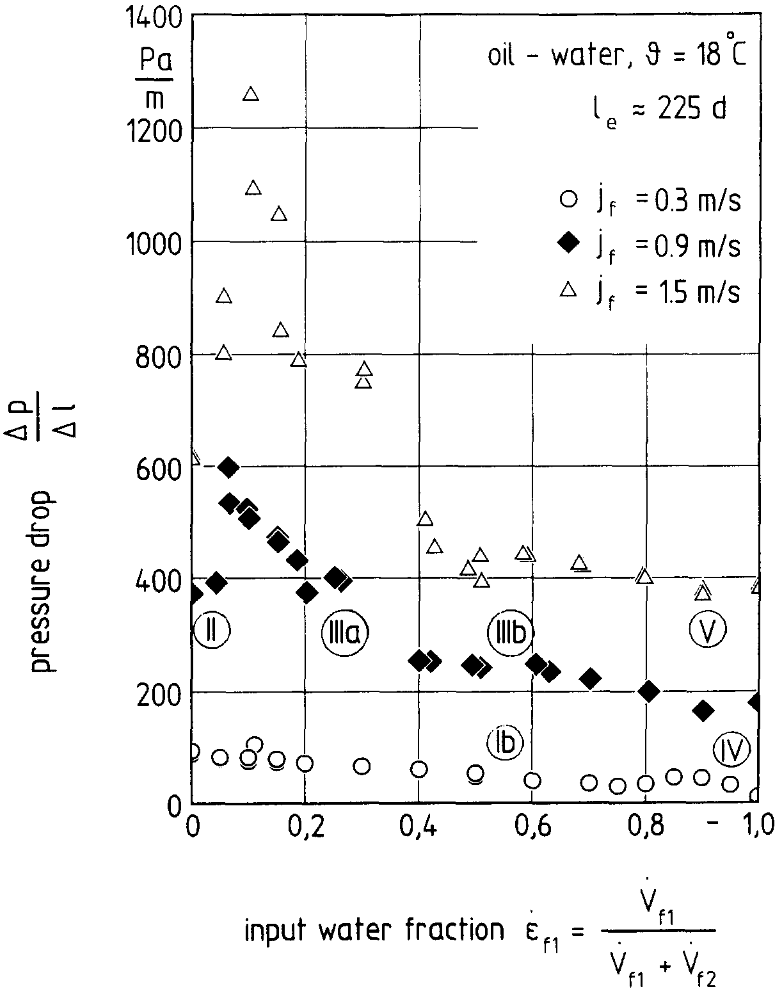

Figure 8. Pressure drop of the two-phase flow of water and oil for a liquid viscosity ratio of $\eta^* = \eta_{f2}/\eta_{f1} = 35$ ($l_e/d \approx 225$).

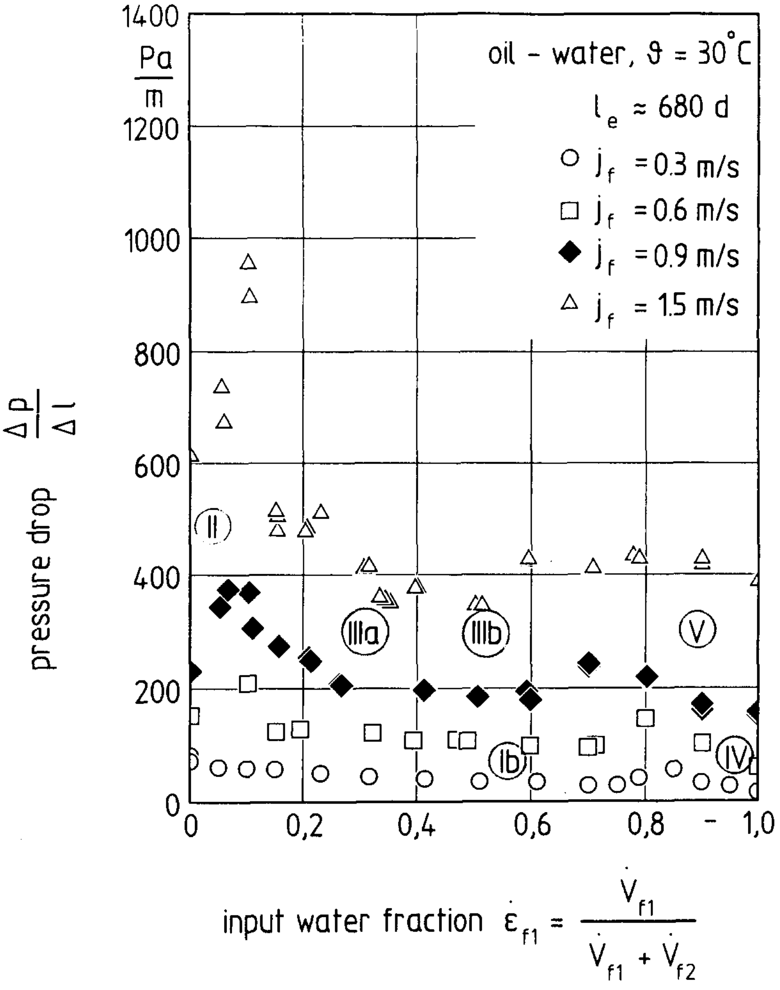

Figure 9. Pressure drop of the two-phase flow of water and oil for a liquid viscosity ratio of $\eta^* = \eta_{f2}/\eta_{f1} = 28$ ($l_e/d \approx 680$).

The dashed line shown in this figure represents the emulsification of the water within the oil predicted by means of [1] with $k_1 = 3$ and $k_1 = 1.2$, the solid line is related to phase inversion within the dispersion layer and calculated by means of [1] applying $k_1 = 1$ and $k_1 = 1.2$, while the dotted line related to the formation of oil-in-water emulsions is predicted by means of [1] with $k_1 = 1$ and $k_2 = -1.2$.

As mentioned above the region of phase inversion, where the external phase inverts from oil to water or vice versa, is associated with region IIIa as well as with region IIIb. The points of phase inversion within the dispersion layers obtained by means of the experimental investigations are given by the boundary between region IIIa and region IIIb. By comparing the solid line calculated by means of [1] with $k_1 = 1$ and $k_2 = 1.2$ and the boundary between the flow regimes IIIa and IIIb similar input water fractions are obtained. As mentioned above phase inversion within the dispersion layers is visually observed for input water fractions in the order of $\dot{\varepsilon}_{f1} \approx 0.33$. In contrast to the results obtained by means of visual observations the measurements of the impendance of the oil–water mixtures flowing in the pipe show a first abrupt change in conductivity for input water fractions in the range from $\dot{\varepsilon}_{f1} \approx 0.05$ (for $j_f = 0.3$ m/s) to $\dot{\varepsilon}_{f1} \approx 0.2$ (for $j_f = 1.5$ m/s) and a second abrupt change in conductivity for input water fractions in the range from $\dot{\varepsilon}_{f1} \approx 0.6$ (for $j_f = 1.5$ m/s) to $\dot{\varepsilon}_{f1} \approx 0.8$ (for $j_f = 0.3$ m/s). This change is contributed to total emulsification of the water phase within the oil phase and vice versa, respectively. The results calculated by means of [1] are in good agreement with the points for the change in the phase distribution determined by means of the conductivity measurements as shown in figure 5.

In the range of mixture velocities less than $j_f = 0.3$ m/s, the stratified flow regime is observed where the water phase and the oil phase are flowing totally separated in layers corresponding to their density (region Ia in figure 5). In the stratified flow regime, an increase of the liquid mixture velocity leads first to a fingering of the water phase into the viscous oil phase. At the end of the fingers water droplets are torn off and dispersed into the oil layer as observed in other studies (eg. Joseph *et al.* 1984b). Otherwise oil encapsulated by the water fingers is entrained into the water layer. This process results in the formation of an interfacial region consisting of oil and water droplets dispersed within the water and the oil layer, respectively (region Ib). Increasing the mixture velocity above $j_f = 0.3$ m/s results in an increasing height of the mixing zone and finally in layers of dispersions filling nearly the whole cross-sectional area of the pipe (region III).

In case of input water fractions less than $\dot{\epsilon}_{f1} < 0.2$, the flow of unstable water-in-oil emulsions is observed which consist of small water droplets nearly homogeneously dispersed within a continuous oil phase in the total cross-sectional area of the pipe (region II). For input water fractions between $\dot{\epsilon}_{f1} = 0.1$ and $\dot{\epsilon}_{f1} = 0.2$, the emulsions look like a viscous gel.

By increasing the input water fraction, dispersions of water-in-oil are observed. The amount of water dispersed within the oil increases with increasing distance from the top of the pipe and reaches a maximum above the bottom of the pipe where a continuous water film is flowing (region IIIa).

An increase of the input water fraction above $\dot{\epsilon}_{f1} = 0.35$ leads to a decreasing height of the layer consisting of a water-in-oil dispersion and an increasing height of the water layer where the upper

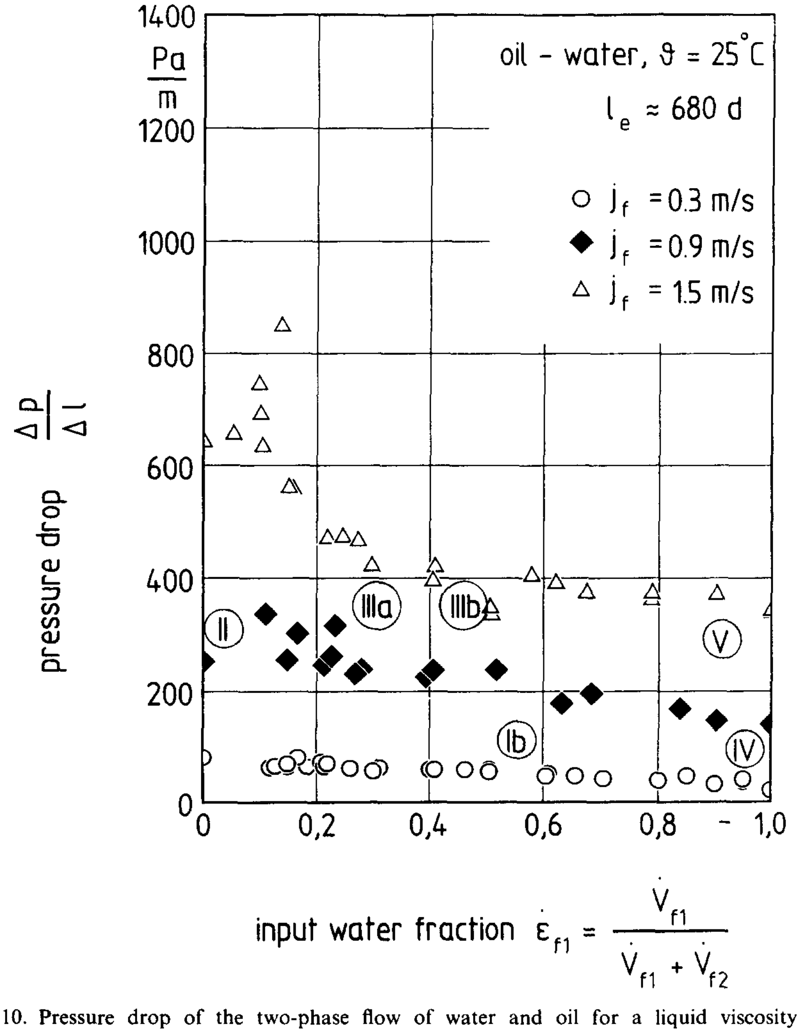

Figure 10. Pressure drop of the two-phase flow of water and oil for a liquid viscosity ratio of $\eta^* = \eta_{f2}/\eta_{f1} = 30$ ($l_e/d \approx 680$).

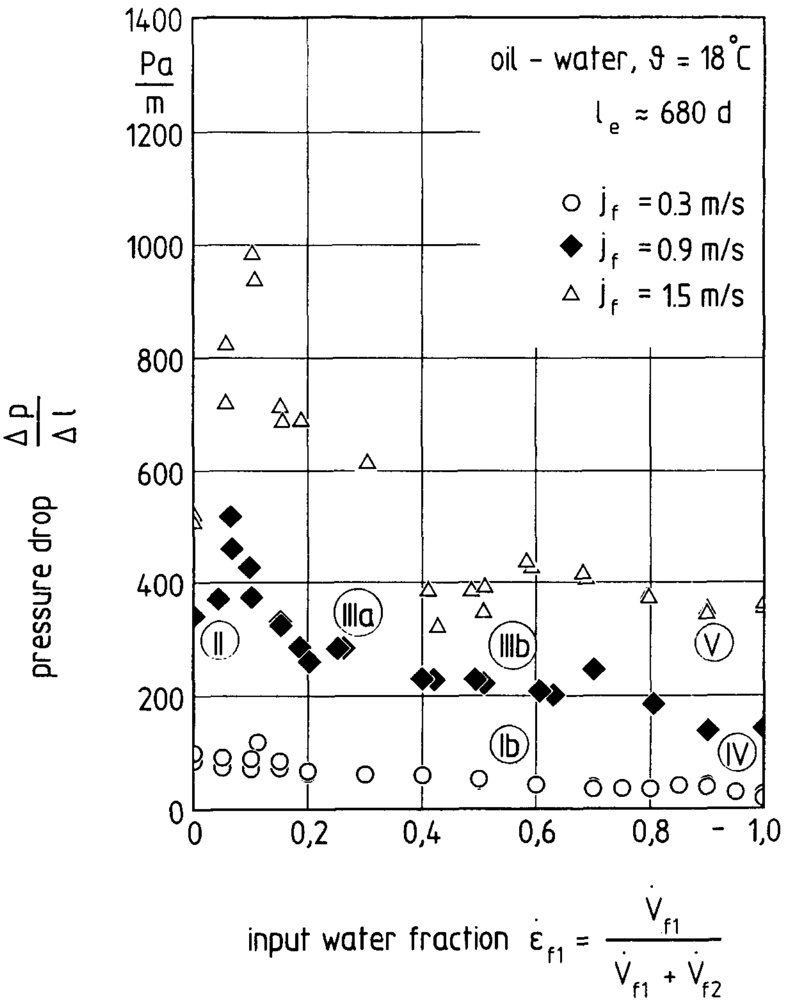

Figure 11. Pressure drop of the two-phase flow of water and oil for a liquid viscosity ratio of $\eta^* = \eta_{f2}/\eta_{f1} = 35$ ($l_e/d \approx 680$).

part of the water layer consists of an oil-in-water dispersion (region IIIb). For liquid mixture velocities less than $j_f = 0.9$ m/s an increase of the input water fraction above $\varepsilon_{f1} > 0.35$ results in the flow regime of oil droplets in water (region IV). In case of higher mixture velocities unstable oil-in-water emulsions are observed (region V).

In the case of a constant liquid mixture velocity, the results shown in figure 5 indicate that total emulsification of the water within the oil and the phase inversion occurs for different input water fractions. As shown in figure 5, the flow regime boundaries predicted by means of [1], are in agreement with those determined in the experimental investigations by means of the conductance measurements and the visual observations, respectively.

4. THE PRESSURE DROP OF THE TWO PHASE FLOW OF OIL AND WATER

The results for the pressure drop of the two-phase flow of oil and water are shown in figures 6–11. The results are obtained for several temperatures of the multiphase mixture and hence different viscosity ratios. Figures 6–8 represent the pressure drop measured in the first leg ($l_e/d \approx 225$) while in figures 9–11, the corresponding results obtained in the second leg ($l_e/d \approx 680$) are shown. In figures 6–11, the roman numbers correspond to the flow regimes shown in figures 3–5.

In the case of the single-phase flow of the oil phase, the transition from the laminar to the turbulent flow regime takes place for superficial oil velocities in the order of $j_{f2} \approx 0.9$ m/s (for 30°C, $\eta_{f2} = 27$ mPas) and $j_{f2} \approx 1.5$ m/s (for 18°C, $\eta_{f2} = 35$ mPas) where for lower superficial oil velocities the oil is flowing laminar. Therefore, for a temperature of $T = 18°\mathrm{C}$, in the case of oil flowing alone in the pipe, the laminar flow regime is always obtained. For a superficial oil velocity of $j_{f2} \approx 1.5$ m/s and a temperature of 18°C the Reynolds number of the oil is $\mathrm{Re}_{f2} = 2144$ and hence in the transition region from the laminar to the turbulent flow regime.

For all flow conditions shown in figures 6–11, the absolute maximum of the pressure drop is measured for input water fractions between $\dot{\epsilon}_{f1} \approx 0.1$ and $\dot{\epsilon}_{f1} \approx 0.2$ and hence for the pipeline flow of water-in-oil emulsions with highest water fractions (figures 4 and 5). In this region the pressure drop is up to twice the pressure drop of the pipeline flow of the pure oil with an equal superficial velocity of $j_{f2} = j_f$.

Similar to the results of other investigations obtained by feeding emulsions into pipelines (eg. Pal 1993) also in the case of emulsions formed from initially separated layers of oil and water the highest values of the pressure drop are measured in the region of water-in-oil emulsions with highest fractions of the dispersed water phase.

For input water fractions in the range from $\dot{\epsilon}_{f1} = 0.35$ to 0.6, the pressure drop of the two-phase flow of oil and water decreases down to values in the order of the pressure drop of pure water. This range of pressure drop reduction is in agreement with the results of Charles *et al.* (1961) mentioned above. The pressure drop reduction is assumed to be caused by a continuous water layer flowing at the pipe wall in the lower cross-sectional area of the pipe. This water layer encapsulate parts of the viscous oil phase, so that viscous dissipation is minimized. Such a drag reduction behaviour in the case of thin water layers flowing above the bottom of the pipe is also reported in other studies (Wyslouzil *et al.* 1987).

After passing the region of a minimum pressure drop, a further increase of the input water fraction results in a second increase of the pressure drop up to a second maximum. The values of this second maximum are less than the values obtained for the pure oil. The second maximum of the pressure drop occurs for input water fractions where the oil is fully dispersed in the water phase and hence the formation of oil-in-water emulsions takes place. This increase of the pressure drop is associated with an inversion from region III to the flow regime of oil-in-water emulsions (region V). After passing the second maximum, a further increase of the input water fraction results in continuously decreasing values of the pressure drop down to the pressure drop of the single phase flow of the water phase.

In the case of input water fractions $\dot{\epsilon}_{f1} < 0.2$ the results shown in figures 6 and 11 indicate, that the pressure drop of the two-phase flow of water-in-oil emulsions is always higher than the pressure drop of the oil flowing alone in the pipeline and thus an oil dominated system is present.

Comparing the results obtained in the first and the second leg, in the first leg generally a higher pressure drop is measured than the one in the second leg. As mentioned above the size of the droplets within the dispersions decreases while the oil–water mixture is flowing downstream. Furthermore, the fraction of the perimeter wetted by layers of pure oil or pure water decreases while the fraction of the perimeter wetted by the dispersion layers increases.

Investigating the pressure drop of two-phase bubble flow in a horizontal pipe, Herringe and Davis (1978) measured a decreasing pressure drop of the water–air mixture with increasing distance from the entrance nozzle. Herringe and Davis (1978) reported that there is a general tendency for the friction factor to be higher in the flow developing region in the upstream test section than far downstream from the entrance nozzle. This is a similar result as observed in the present study for the two-phase flow of two immiscible liquids, where the pressure drop of the oil–water mixture decreases with increasing distance from the entrance nozzle. The change in the droplet size, mentioned in section 3, indicates, that the two-phase flow of oil and water is still developing behind an entrance length of $l_e/d = 225$ while far downstream from the entrance nozzle ($l_e/d = 680$), no significant change in the pressure drop is observed.

Comparing the results shown in figures 6–11, the effect of the viscosity ratio on the input water fraction required for emulsification does not seem to be significant in the viscosity range investigated. This is confirmed by the results of the investigation carried out by Charles *et al.* (1961) indicating that there is no significant effect on the flow regime transition boundaries by changing the viscosity ratio by a factor of 72. Otherwise, the results reported by Arirachakaran *et al.* (1989) indicate that the formation of water-in-oil emulsions is influenced by greater changes in the viscosity ratio.

5. CONCLUSION

In this paper the results of experimental investigations of the two-phase flow of oil and water without any added surfactant in a horizontal pipeline are presented. By feeding the immiscible liquids into the pipeline in layers corresponding to their densities the formation of unstable dispersions and unstable emulsions from initially separated layers is observed. According to the experimental results for the flow regimes and the pressure drop of the oil–water mixtures, different flow regimes of dispersions are distinguished.

- In the case of water-in-oil emulsions, maximum values of the pressure drop of the pipeline flow of water and oil are observed.
- In the flow region, where above the bottom of the pipe a pure water layer and layers of water-in-oil and oil-in-water dispersions are flowing, drag reduction is observed. The minimum pressure drop of the flow of dispersions is of the order of the pressure drop of the pure water phase flowing alone in the pipe.
- Phase inversion is observed within the dispersion layer and hence in a restricted part of the cross-sectional area of the pipe. The occurrence of phase inversion and the total emulsification of one liquid phase within the other is observed for different input water fractions.
- In case of oil-in-water emulsions filling the whole cross-sectional area of the pipe the pressure drop is between the pressure drop of the pipeline flow of the pure oil phase and the flow of the pure water phase.

According to the results of the present study, it is recommended that in the case of a lack of knowledge of the behaviour of the two-phase flow of oil and water, the order of the pressure drop of the two-phase flow should be approximated by the pressure drop of the water phase in the case of oil-in-water emulsions and by the pressure drop of the oil phase in the case of water-in-oil emulsions. In the region of layers of pure phases as well as dispersions, a first approximation for the pressure drop of these layers may be given by the sum of the pressure drops of the single phase flow of the water phase and the oil phase weighted by the input water and the input oil fraction, respectively.

In order to distinguish between a water and an oil continuous system, equations are necessary for predicting the critical input water fractions resulting in oil-in-water and water-in-oil emulsions.

Acknowledgements—The authors wish to acknowledge the financial support of the BMFT (Bundesministerium für Forschung und Technologie) for a programme on technical development of Multiphase Transportation Systems. Thanks are also extended to the German Shell Company for its donation of the oil used in this study.

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