THE EFFECTS OF PRODUCTION RATE AND CHOKE SIZE ON EMULSION STABILITY

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ABSTRACT

When oil is produced under high water-cut conditions, knowledge of the oil-droplet-size distribution downstream of the choke valve is required to optimise the separation process.

In this paper, laboratory experiments to investigate the oil-droplet-size distribution of an oil-water mixture downstream of a restriction in a pipe are described. A relation is provided to estimate the maximum stable droplet size downstream of an orifice for a given flow rate and pressure drop. Droplets larger than this maximum stable size can exist downstream of the restriction. The droplet size after break-up is a function of the droplet size upstream. This effect of the original droplet size can be understood by considering that a droplet does not stay long enough in the turbulent zone of the orifice to break up to its maximum stable size. A theoretical break-up model is described, which incorporates the time needed for a droplet to break up and the residence time of that droplet in the restriction.

The effect of the geometry of the restriction on droplet break-up has also been investigated. Generally, for a given flow rate and pressure drop, a needle valve causes less break-up than an orifice. Furthermore, for a high energy dissipation rate per unit mass and small droplets upstream of the restriction, two valves in series cause less break-up than one single valve. This beneficial effect decreases with decreasing energy dissipation rate and increasing droplet size upstream. It can be concluded that the use of a different choke-valve geometry can diminish droplet break-up, which results in an increase in separation efficiency.

INTRODUCTION

A problem that is often encountered in oil production, is the large amount of water that is produced simultaneously with the oil. Most wells have a tendency for increasing water cut with increasing lifetime. The water cut can reach very high values; in the North Sea, for example, wells producing at a water cut up to 95 % are not uncommon. At these high percentages, the oil and water are produced as an oil-in-water dispersion, which means that oil is present in the water in the form of droplets. Under these circumstances large volumes of produced fluids have to be treated, which can be a costly affair.

In conventional production systems the produced oil-water mixture is separated at the surface. In general is valid that the effort needed for oil-water separation increases with decreasing droplet sizes in the mixture [1]. In case the separation process is based on the density difference between oil and water, which is for example the case in a plate separator, hydrocyclone and centrifuge, the separation efficiency rapidly decreases when droplets smaller than a certain critical diameter enter the separator. A typical critical diameter for a plate separator is of the order of 30 μm, and for a centrifuge this diameter can be as low as 5 μm. Part of the droplets smaller than this critical value remain in the water, downstream of the separator, and can cause severe problems. For example: to be allowed to dispose the produced water in the sea, the water has to meet stringent environmental demands, which means that the oil concentration has to be below a certain value, typically of the order of 30 parts per million. Furthermore, in case of re-injection of the produced water into a reservoir, the injectivity decreases when oil droplets are present in the water [2], which results in an increase in effort and costs for the handling of produced water.

A topic that is of interest with regard to high water-cut wells, is the size of the produced oil droplets. Janssen and Harris [3] investigated the morphology of oil-water mixtures under high water-cut conditions, as they flow out of the reservoir into the well. From their measurements it can be concluded that, even at high production rates, the produced oil droplets are of the order of tens of microns. This indicates that at the bottom of the well droplets have sizes, which are generally larger than the critical diameter of a separator. Field measurements show that droplets at the entrance of the separation equipment at the surface can be smaller than 5 μm [4], which is much smaller than those present at the bottom of the well. From this result it has to be concluded that oil droplets break up somewhere between the bottom of the well and the entrance of the separator. It is believed that break-up of oil droplets in the production system is governed by turbulent forces [5]. Therefore the most likely location where the break-up takes place is

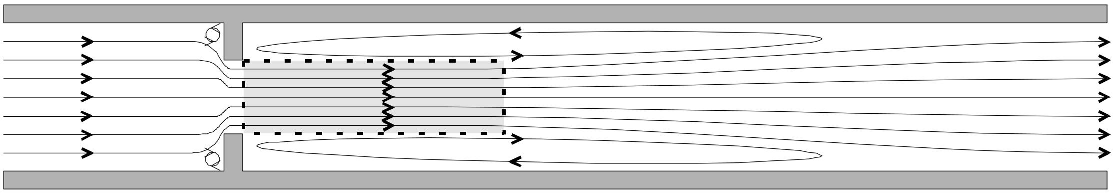

***Figure 1:** Schematic representation of fluid flow through a circular orifice in a pipe.*

the position where the turbulence is the most intense, which is equivalent to where the most energy is dissipated. In most production systems this is the choke valve [6].

In this paper, laboratory experiments on droplet break-up in valves and restrictions in pipes are presented, and a theoretical model describing the break-up process in the choke valve is given.

THEORY

The function of the choke valve in a production system is to regulate the production rate and to decrease the pressure in the system, downstream of the valve. This decrease in pressure is desirable for several reasons. One of these reasons is that a low pressure in the topside production system, does not put high demands, as far as safety is concerned, on the construction of the separator. The main principle on which the choke valve is based, is that the fluids are forced through a restriction in the flowline. The fluids accelerate and, because of the large velocity gradients, the turbulence of the flow intensifies. Due to this increased turbulent energy dissipation, a pressure drop across the valve occurs, and this pressure drop is used to regulate the production rate.

Nowadays, in production systems, various choke valve designs are being used, for example the conventional fixed bean valve, the multiple orifice valve, and plug and cage type valves. In our laboratory experiments we have, in the first instance, not looked at the various valve designs, but simply modelled the choke valve as a circular orifice in a pipe. In Fig. 1 this configuration has been sketched.

The flow is forced through a small flow area, which results in the acceleration of the fluid. Upstream and downstream of the orifice, recirculation zones develop. Most of the energy is dissipated in the shaded volume indicated in Fig. 1, which has according to measurements a length of approximately 2.5 pipe diameters [7]. Based on this approximation of the flow field, an expression for the mean energy dissipation rate per unit mass in the turbulent zone, $\bar{e}$, can be derived [8]:

$$\bar{e} = \frac{?p \cdot U_o}{?_c \cdot 2.5D_p} \qquad (1)$$

where Dp is the pressure drop across the orifice, U_o the mean fluid velocity in the orifice, r_c the density of the continuous phase, and D_p the pipe diameter. The energy dissipation rate per unit mass is an important quantity for the description of turbulence and turbulent break-up.

Turbulent break-up

To be able to estimate the oil-droplet size in a turbulent flow, Hinze [9] derived a relation, which correlates the maximum stable droplet diameter in a turbulent flow to the energy dissipation rate per unit mass. He simplified the break-up process by taking only two stresses into consideration. Firstly, the interfacial stress acts in such a way that the droplet at rest obtains a spherical shape. This interfacial stress is proportional to s/d, where s is the interfacial tension and d the droplet diameter. Secondly, the turbulent velocity fluctuations around the droplet, which are induced by turbulent eddies, result in an external stress, t, equal to the dynamic pressure difference across the droplet diameter. This pressure difference causes the droplet to deform. For τ is valid:

$$t \propto r_c\left[\Delta U(d)\right]^2 \propto r_c(ed)^{2/3} \qquad (2)$$

To obtain the right-hand side of Eq. 2, the relation that states that the velocity difference, DU, across a distance d, is equal to $1.41(ed)^{1/3}$, has been used. This relation can be derived from turbulence theory. For the maximum stable droplet diameter, the interfacial stress and the dynamic pressure fluctuations just balance, and from this can be derived that:

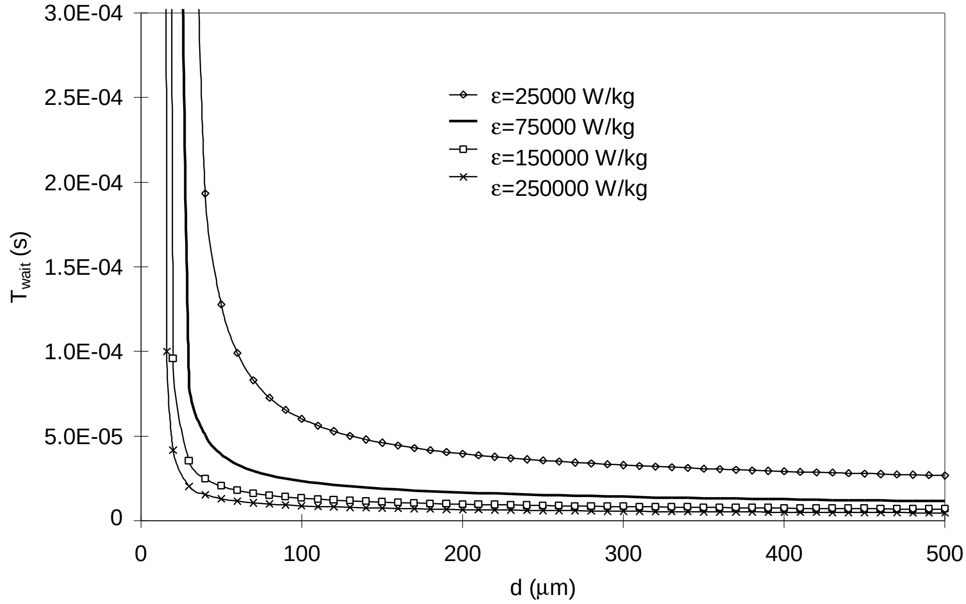

Figure 2: *The waiting time (Eq. 7) between two break-up events as a function of the droplet diameter for various energy dissipation rates per unit mass. The interfacial tension used for calculating T_{wait} is equal to 35 mN/m.*

$$d_{max} = C\left(\frac{s}{r_c}\right)^{3/5} e^{-2/5} \qquad (3)$$

From experimental data, Hinze found that the constant *C* is equal to 0.725. It should be noted that in this approach the effect of the dispersed phase viscosity is neglected.

A basic assumption which has been made for the derivation of Eq. 3, is that the droplet is allowed sufficient time to break up to a size smaller than or equal to d_{max}. For the case of turbulent break-up in flow through valves, this assumption needs closer investigation. Measurements on droplet break-up in orifices show that droplet sizes downstream of the restriction are dependent on the sizes upstream [8,10]. It is argued that this effect of the sizes upstream can be explained by the fact that droplets are not allowed sufficient time to break up to d_{max}. To verify this statement, the various time scales involved in the break-up process have to be determined.

The residence time of droplets in the turbulent zone, T_{res}, can be estimated as follows:

$$T_{res} \cong \frac{\Delta x}{U_o} = \frac{2.5 \cdot p \cdot D_p^{\,3}\, b^2}{4 \cdot Q} \qquad (4)$$

where *Q* is the volume flow rate, and b the ratio between the orifice diameter and the pipe diameter.
The time needed for a droplet to decrease in size to d_{max} is built up of several contributions. In the first place a droplet entering the turbulent zone will not immediately break up. It will take some time before the droplet interacts with an eddy of sufficiently high energy to be able to break up. Furthermore, the droplet has to deform before it breaks up, and this also takes time. Finally, a droplet might have to break up several times before it has decreased to a stable size.

Droplet-eddy interaction

In their article, Luo and Svendsen [11] derive an expression for the break-up rate of droplets in a turbulent flow. To arrive at this expression, they make the following assumptions. Firstly, the turbulence is assumed to be homogeneously isotropic. In general, turbulence does not satisfy this condition, but on a small enough scale, e.g. the droplet scale, this assumption is valid. Secondly the break-up mechanism is assumed to be binary break-up. This assumption is generally made in break-up theory, and experimental data of Hesketh [12] shows that it is valid for turbulent pipe flow. Thirdly, the break-up volume fraction, to which the droplet breaks up, is assumed to be a stochastic variable. The fourth assumption is that eddies act on the droplet individually. Basically, this means that only eddies of sufficiently high energy are able to break up a droplet: the energy of an eddy has to be larger than the increase in interfacial energy of the droplet in order to cause break-up. The fifth assumption is that only eddies smaller than the droplet diameter contribute to the break-up process. Eddies larger than the droplet translate rather than deform the droplet.

To derive the expression for the break-up rate, first the collision frequency between eddies and the droplet is calculated. This collision frequency is then multiplied with the probability that the eddy has an energy larger than the minimum energy required for break-up, which is the increase in interfacial energy of the droplet. All this results in the following relation:

$$\Omega_b(V:Vf_{bV}) = \int_{l_{min}}^{d} 0.923 e^{1/3} \frac{(d+l)^2}{l^{11/3}} \exp\left(- \frac{6d^2 s\,[f_{bV}^{2/3} + (1-f_{bV})^{2/3} - 1]}{r_c e^{2/3} l^{11/3}} \right) dl \qquad (5)$$

In Eq. 5, $W_b(V{:}Vf_{bV})$ is the break-up rate of a droplet of volume V, and diameter d, into two daughter droplets of volumes Vf_{bV} and $V(1-f_{bV})$. Furthermore, l is the eddy size, and l_{min} the smallest eddy in the inertial subrange of turbulence, which still contributes to the break-up process. The integral in Eq. 5 can be rearranged using incomplete gamma functions, and can then be calculated.

The total break-up rate of a droplet, independently of the volume fraction to which it breaks up, can be found by integrating Eq. 5 over all possible break-up fractions, which is either $0<f_{bV}<0.5$ or $0.5<f_{bV}<1$:

$$\Omega_{b,tot}(V) = \int_{0.5}^{1} \Omega_b(V:Vf_{bV})\,df_{bV} \qquad (6)$$

The average period between two break-up events for a droplet of volume V is equal to the inverse of Eq. 6:

$$T_{wait}(V) = \frac{1}{\Omega_{b,tot}(V)} \qquad (7)$$

In Fig. 2, T_{wait} has been plotted as a function of the droplet diameter for various energy dissipation rates. It can be observed that the waiting time between two break-up events increases with decreasing droplet size and energy dissipation rate.

The expression in Eq. 5 can be interpreted as the distribution function of the break-up volume fraction for a droplet of volume V for a given energy dissipation rate. With the help of Eq. 6 it is possible to calculate from Eq. 5 the mean break-up volume fraction to which a droplet breaks up:

$$\bar{f}_{bV}(V) = \frac{\int_{0.5}^{1} f_{bV} \cdot \Omega_b(V:Vf_{bV})\,df_{bV}}{\Omega_{b,tot}(V)} \qquad (8)$$

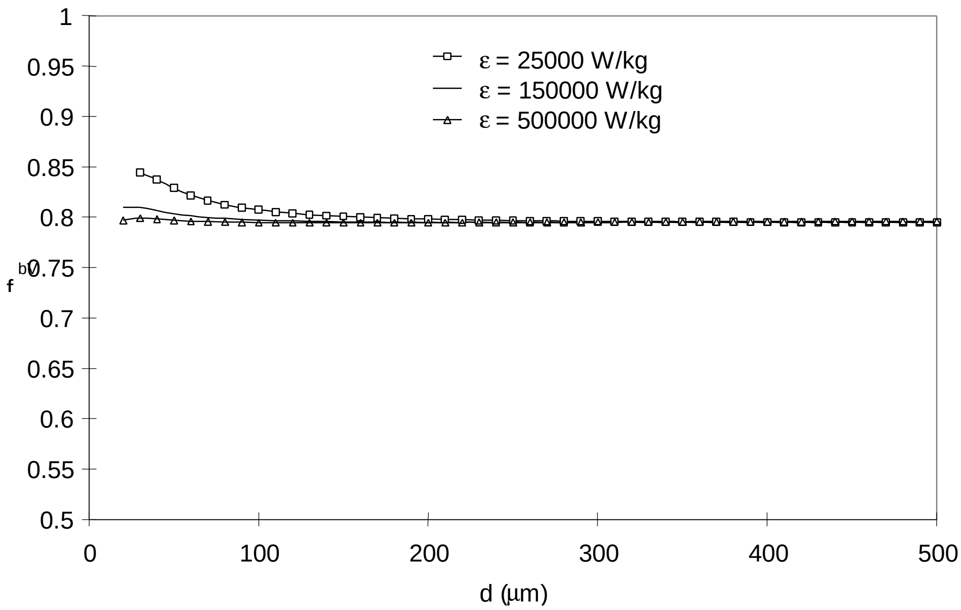

Figure 3: *The mean break-up volume fraction (Eq. 8) as function of the droplet diameter for three different energy dissipation rates per unit mass (s=35mN/m).*

In Fig. 3 the mean break-up volume fraction as a function of the droplet diameter has been plotted for various energy dissipation rates.
It can be seen in Fig. 3 that the mean break-up volume fraction is approximately 0.8, and increases slightly for decreasing droplet diameter. This implies that on average a droplet of diameter *d* will break up to two daughter droplets with diameter *0.93·d* and *0.58·d*, respectively.

Droplet deformation

Now that expressions for the waiting time and the mean break-up volume fraction have been derived, the only time scale that has to be determined in order to estimate the time needed for a droplet to decrease in size, is the break-up time. In his article Das [13] provides a theoretical model of the deformation and break-up process of a droplet in a turbulent flow. He uses the Voigt model to describe the deformation process:

$$\frac{s}{d}q + m_d \frac{dq}{dt} = t \qquad (9)$$

where q is the deformation, which can be seen as the dimensionless increase in interfacial area. The droplet is deformed by an external stress, τ (Eq. 2), which is induced by the velocity fluctuations around the droplet. In Eq. 9 it can be seen that the interfacial tension acts as a spring, opposing deformation. The dispersed phase viscosity acts as a damper, opposing internal flow induced by the deformation. Equation 9 can be solved for q as a function of time. Das argues that a droplet breaks up when the deformation reaches unity. From this assumption the time needed for a droplet to break up, T_b, can be calculated.

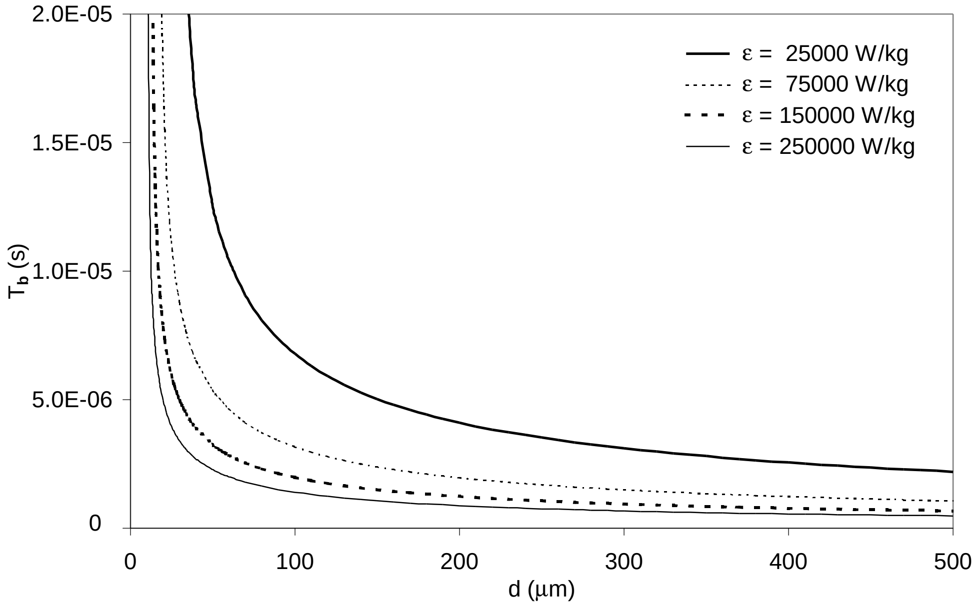

Figure 4: *The break-up time (Eq. 10) as a function of the droplet diameter for four different energy dissipation rates per unit mass (m_d = 20 mPa×s and s = 35 mN/m).*

$$\begin{aligned} T_b &= \frac{dm_d}{s} \ln\left(\frac{t}{t - \frac{s}{d}}\right) \\ &= \frac{dm_d}{s} \ln\left(\frac{1.7\, r_c (ed)^{2/3}}{1.7\, r_c (ed)^{2/3} - \frac{s}{d}}\right) \end{aligned} \qquad (10)$$

A droplet will only break up when the eddy that is deforming the droplet, acts on the droplet for a period longer than the break-up time of that droplet. This period during which an eddy acts on a droplet is assumed to be equal to the lifetime of that eddy. From turbulence theory it can be found that the lifetime, T_{life}, of an eddy of size λ, is given by:

$$T_{life} = \frac{l}{\Delta U(\,l\,)} = \frac{l^{2/3}}{1.41 \cdot e^{1/3}} \qquad (11)$$

As long as the eddy of size equal to the droplet diameter has a lifetime longer than the break-up time of that droplet, the droplet breaks up. For the maximum stable droplet diameter is valid that the lifetime of an eddy of the droplet size is just equal to the break-up time of that droplet. By stating that T_b=T_{life} (in the non-viscous limit) the expression given in Eq. 3 can be obtained for d_{max}. Using the value of 0.725, which Hinze found from experiments, the value of 1.7 in the right-hand side of Eq. 10 can be obtained. In Fig. 4, the break-up time has been plotted as a function of the droplet diameter, for various energy dissipation rates.
From Fig. 4 it can be seen that the break-up time increases with decreasing droplet diameter and decreasing energy dissipation rate.

Break-up model

Now that all the relevant parameters have been determined, a simplified model of the break-up process can be build up. The basic idea behind the model is that a droplet is followed during its travel through the turbulent zone in the orifice. It is assumed that droplets follow the streamlines. Measurements show [7] that this approximately means that a droplet moves parallel to the pipe axis with a speed equal to the mean velocity in the orifice, U_o. For a given flow rate and orifice size, the mean energy dissipation rate per unit mass (Eq. 1) is determined. It is assumed that this dissipation rate is uniformly distributed throughout the turbulent zone, which is the shaded volume in Fig. 1. When a droplet enters the turbulent zone it first has to wait a certain amount of time, T_{wait} (Eq. 7), before it collides with an eddy that is capable of breaking up the droplet. During this period the droplet has moved over a distance $U_o{\times}T_{wait}$. Then the break-up time of the droplet is determined (Eq. 10), and in case the lifetime (Eq. 11) of the deforming eddy is larger than the break-up time, the droplet will break up during a period T_b. During the deformation, which eventually leads to break-up, the droplet has travelled a distance $U_o{\times}T_b$. This break-up event results in two daughter droplets of diameters 0.93 and 0.58 times the original droplet diameter. Next, only the largest daughter droplet is being monitored. For this droplet T_{wait} is calculated, and the whole cycle is repeated. Again, after break-up, only the largest daughter droplet is monitored. This is repeated until the droplet has left the turbulent zone. In this way it is possible to calculate the largest droplet diameter resulting from the original droplet that entered the orifice.

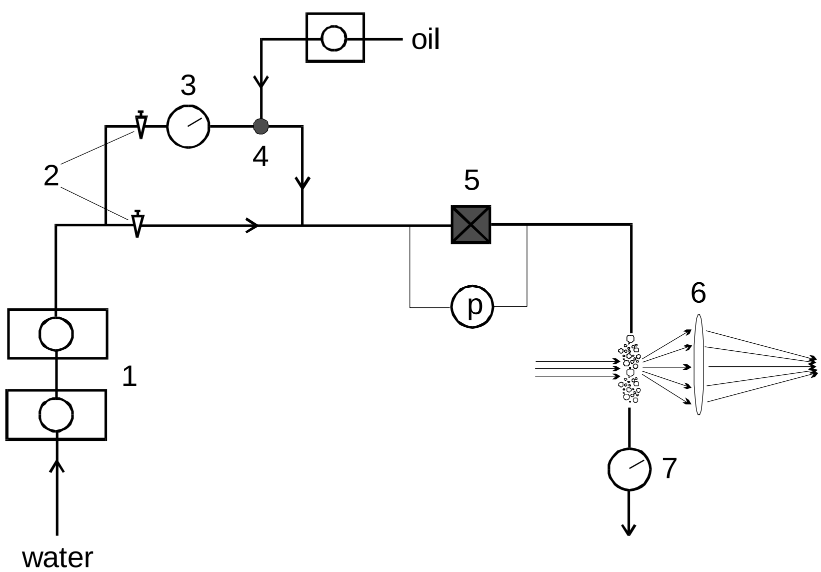

Figure 5: *A schematic representation of the set-up. The components of the set-up are explained in the text.*

EXPERIMENTAL SET-UP

For the experiments on droplet break-up in a restriction, the set-up sketched in Fig. 5 has been used. Two Verder gear pumps (1) are used to pump water through the set-up. The two pumps are placed in series in order to obtain a sufficiently high pressure in the set-up. The maximum flow rate is 1.8 l/min and the maximum pressure 10 bars. The pipes through which the water flows, have an internal diameter of 4.5 mm. Downstream of the pumps, part of the water flow is side-tracked. The flow rate through this side-track is measured (3), and can be adjusted using two control valves (2). By means of a three-way needle valve oil is dispersed in the water. The oil is pumped by a Gilson plunger pump. The oil-water mixture is redirected to the main stream, and then flows through the restriction (5), across which the pressure drop is measured. The concentration of oil in the mixture is typically around 0.1 volume %. The droplet-size distribution upstream of the restriction is mainly a function of the flow rate through the side-track. The higher this flow rate, the smaller the droplets. Using the two control valves, the flow rate through the side-track can be regulated independently of the main flow rate. The oil-droplet-size distribution is measured using a Malvern particle sizer (6), type 3600 E. The measurement technique is based on laser light diffraction. Before the oil-water mixture is disposed in a separator vessel, the main flow rate is measured (7). A feature of the set-up, which has not been displayed in Fig. 5, is a bypass of the restriction. By simply opening or closing two ball valves, a piece of undistorted pipe can be chosen to be flown through. In this way the injected droplets are not broken up and, consequently, the injected droplet-size distribution can be measured.

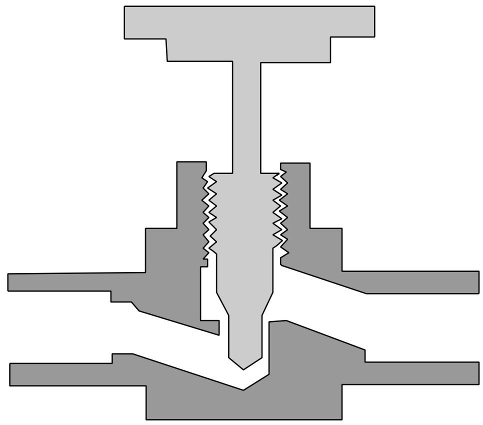

Figure 6: *Schematic representation of a Swagelock[tm] valve, 'integral bonnet needle valve', inside diameter 4.5 mm. Flow direction is from left to right.*

For the experiments three types of restrictions have been used. The first type is an orifice (Fig. 1), of which the diameter varied between 1.0 and 3.0 mm in steps of 0.5 mm. The second type is a needle valve, as shown in Fig. 6. The third type of restriction that has been used, is two needle valves in series. The combination of these two valves is considered to be one restriction.

To be able to compare the three types of restrictions, the valves have been closed to such an extend that they create the same pressure drop at a given flow rate as the orifice does. In this way for a given flow rate and pressure drop the droplet-size distribution downstream of the three different types of restrictions can be compared.

In the experiments the continuous phase is de-mineralised water at room temperature, and as dispersed phase either Shell Vitrea 9, Vitrea 46, or n-heptane has been used. The properties of these three dispersed phases are shown in table 1.

	n-heptane	Vitrea 9	Vitrea 46
Viscosity (mPas)	0.4	18	150
Density (kg/m^3)	684	867	876
IFT (mN/m)	43.7	34.0	34.2

Table 1: *Viscosity, density and interfacial tension (IFT) under experimental conditions.*

RESULTS AND DISCUSSION

The experiments have been carried out in the following way. For a given main flow rate, orifice size and flow rate through the side-track, the droplet-size distribution downstream of the orifice is measured. In the consecutive run, the main flow rate and orifice size (and consequently the pressure drop) are kept constant, and only the flow rate through the side-track is increased. In this way smaller droplets are injected, while leaving all other conditions unaltered. By measuring the size distribution downstream of the orifice, the effect of injected droplet size on the distribution downstream is investigated. From the injected distribution and the distribution after break-up the d_{95} is determined. This is the diameter below which 95 volume % of the dispersed phase is present. It is believed that d_{95} is a good approximation of the maximum droplet diameter of the distribution. The results of a representative set of runs under a given condition are given in Fig. 7.

In Fig. 7 it can clearly be seen that there is an effect of the injected droplet size on the size downstream of the orifice. With decreasing injected droplet sizes, the droplet sizes downstream of the orifice

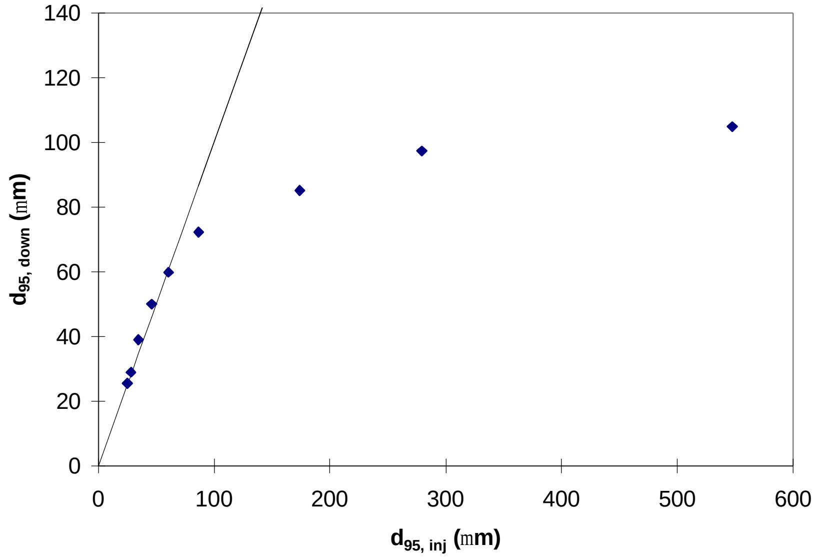

Figure 7: *The effect of injected droplet-size distribution (characterised by $d_{95,\ inj}$) on the distribution downstream of the orifice ($d_{95,\ down}$). The flow rate through the orifice of 1.5 mm is 0.73 l/min,*

decrease. This effect has also been observed by other investigators [10].

Injected droplet-size distributions with sufficiently low $d_{95,\ inj}$, do not change at all. The largest d_{95} for which this happens is called $d_{95,\ stable}$, and corresponds to the distribution with the largest stable droplets. In Fig. 7 this $d_{95,\ stable}$, can be determined by approximating the diameter at which the measured curve starts deviating from the line given by $d_{95,\ inj} = d_{95,\ down}$. For the case shown in Fig. 7, $d_{95,\ stable}$ is approximately equal to 65 µm.

For all three dispersed phases that have been used in our experiments, the $d_{95,\ stable}$ can be determined for various flow rates and orifice sizes. In Fig. 8 these values have been plotted as function of the expression given in Eq. 3.

One of the conclusions that can be drawn based upon Fig. 8, is that the relation given in Eq. 3, is suitable for the description of the maximum stable droplet size in a turbulent dispersion. There is, however, some scatter of the data around the fitted straight lines.

Furthermore it can be seen in Fig. 8 that for a given energy dissipation rate (i.e. flow rate and orifice size) the droplet size increases with increasing dispersed phase viscosity. Many authors [9,14] have already predicted this effect of the dispersed phase viscosity. The effect can be understood by considering that the resistance against droplet deformation and internal flow increases with increasing dispersed phase viscosity. Therefore, with increasing viscosity the energy needed for deformation increases, and consequently, at a given energy dissipation rate, less energy will be available for the increase in interfacial area. This results in larger droplets.

Since the viscosity of n-heptane is very low, the data obtained for this dispersed phase can be treated as the non-viscous limit. Hinze predicted that the slope of the line that fits the n-heptane data, should be equal to 0.725. Based on a theoretical description of the droplet break-up Sevik and Park [15] derived that the slope in the non-viscous limit should be equal to 0.74. From our experiments we find that this slope is equal to 0.87. This value is in the order of the predictions made by Hinze and Sevik, indicating that our approach of the break-up process in restrictions is suitable. An explanation for the somewhat higher value of slope is that the value of the mean energy dissipation rate per unit mass that we use (Eq. 1) is too high. In case the length of the dissipation zone in an orifice is larger than 2.5 pipe diameters, the mean energy dissipation rate becomes smaller and consequently the slope of the fitted line decreases.

From the consideration given above, it can be concluded that Eq. 3 provides a suitable relation for the prediction of the largest stable d_{95}. However, in Fig. 7 it is shown that droplet-size distributions with a d_{95}

larger than $d_{95,\ stable}$ can exist downstream of the orifice. To be able to predict the size distribution downstream of the orifice, it is important to understand the break-up process as it takes place inside the orifice. For this purpose the break-up model, which has been described in the theory section, can be used. In Fig. 9 the results of the break-up model are compared with a measurement. It should be noted that for the experiments the d_{95}*'s* of the distributions have been plotted, and for the model the *diameter* of the injected droplet and that of the largest droplet resulting from this droplet.

The most striking phenomenon that can be observed in Fig. 9 is that the simulation predicts smaller droplet sizes than actually measured. An explanation is that the effect of the dispersed phase viscosity is not correctly incorporated in the model. This viscosity enters the model in the expression for the break-up

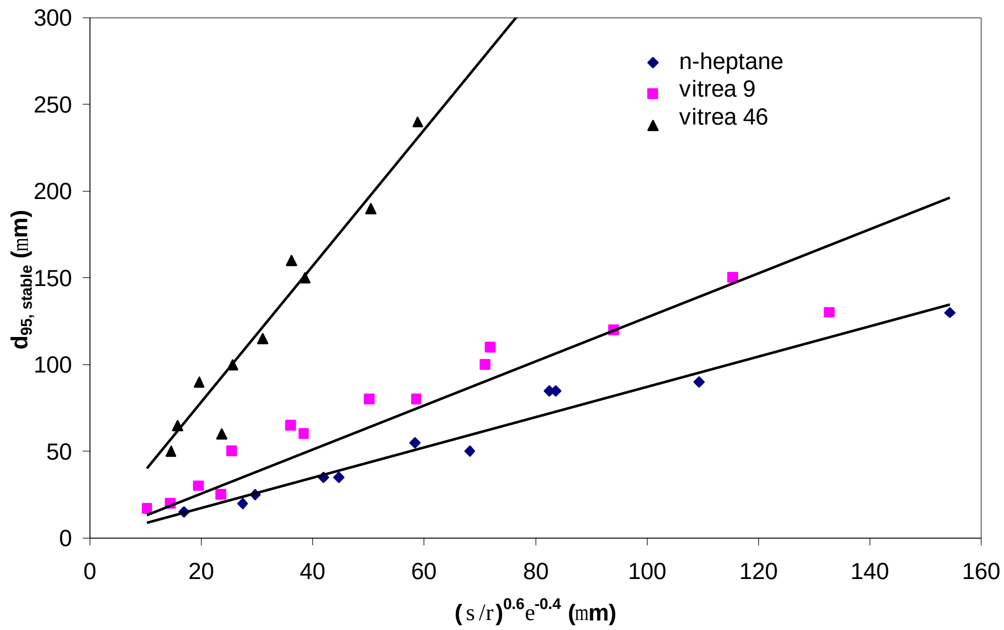

Figure 8: *The* $d_{95,\ stable}$ *for three different types of dispersed phases, has been plotted as function of the expression given in Eq. 3.*

time (Eq. 10). The diameter where the simulations start deviating from the line d_{inj} = d_{down}, is determined by the equation T_b = T_{life} (Eqs. 10 and 11). In words this equation means that the eddy, which deforms the largest stable droplet, lives just long enough to break up the droplet. As argued before, in the non-viscous limit the equation transforms into the relation derived by Hinze (Eq. 3), which fits our experimental data quite well. An adjustment in the expression for the break-up time will result in a change of the value for which the calculated diameters start deviating from the line d_{inj} = d_{down}. By adapting the expression for the break-up time, the simulation can be made to fit the experimental data better.

Besides the difference in sizes, the simulation is able to predict the trend of the experimental data. The predicted effect of the injected droplet size is very similar to the measured effect: the model shows that droplets larger than d_{max} can be present downstream of the orifice. This indicates that by looking at the break-up process in terms of time scales, valuable knowledge about the process can be obtained.

Another type of experiments that has been conducted, is where we have compared the three different types of restrictions in terms of break-up. For a given flow rate and pressure drop across the restriction, a set of experimental runs has been carried out for each type of restriction. In Fig. 10 the results of the experiments for an orifice of diameter 1.0 mm, a needle valve and two needle valves in series at a flow rate of 0.48 l/min, and consequently a pressure drop of 0.9 bar, have been compared.

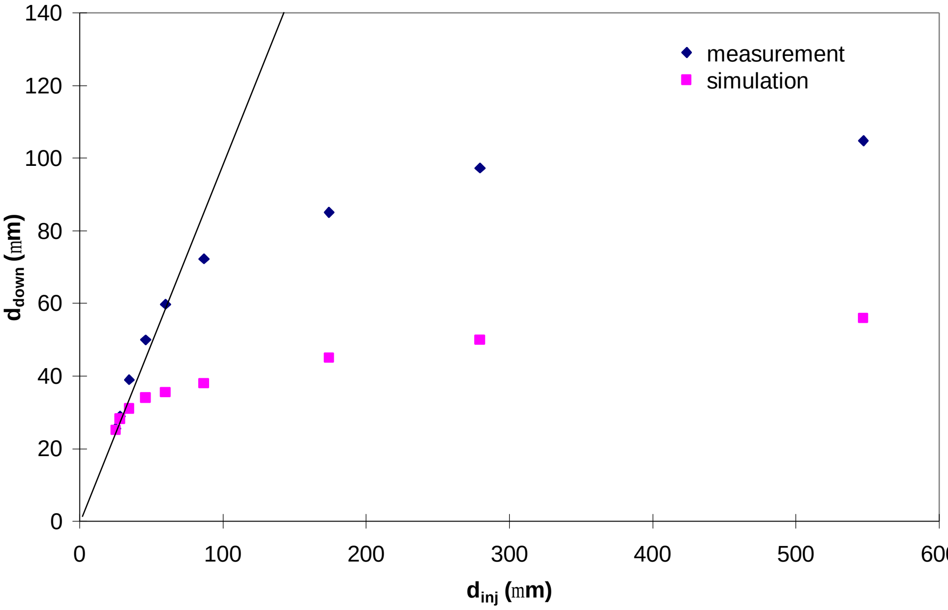

Figure 9: *Comparison between measurements and the results predicted by the break-up model described in the theory section (dispersed phase: Vitrea 9, orifice size: 1.5 mm, flow rate: 0.73 l/min).*

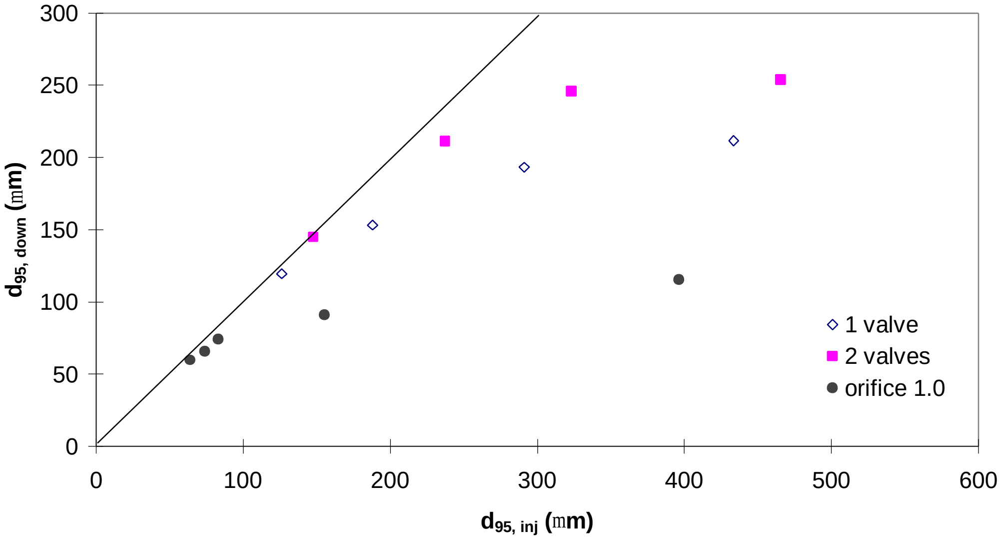

Figure 10: *Comparison of the break-up of oil droplets (Vitrea 46) in the 1.0 mm orifice, the needle valve and two valves in series. For all restrictions the flow rate is 0.48 l/min and the pressure drop is 0.9 bar.*

In Fig. 10 several interesting features can be observed. Firstly, there is a clear effect of the geometry of the restriction on the droplet size downstream of the restriction. Under identical conditions the needle valve causes less break-up than the orifice. An explanation for this result is that the flow inside the valve is different than in the orifice. In case the volume over which the valve dissipates the energy is larger than this volume in an orifice, the mean energy dissipation rate per unit mass in the valve is lower than in the orifice. Consequently, for identical flow rate and pressure drop, the forces acting on a droplet will be smaller in a valve than in an orifice, resulting in less break-up. This explanation is open for discussion since we have not been able to measure the flow inside the valve and orifice in our set-up. With respect to this, the use of computational fluid dynamics to simulate the flow field inside the restrictions can be a useful tool to understand the experiments.

A second interesting result shown in Fig. 10 is that two valves in series result in less break-up than one single valve. It should be noted that the total pressure drop across the two valves in series is equal to the pressure drop across the single valve. The difference in droplet size downstream of the restriction can be explained by considering that in case of the two valves in series, the pressure drop across each individual valve is half the total pressure drop. This is achieved by opening the valves slightly more than

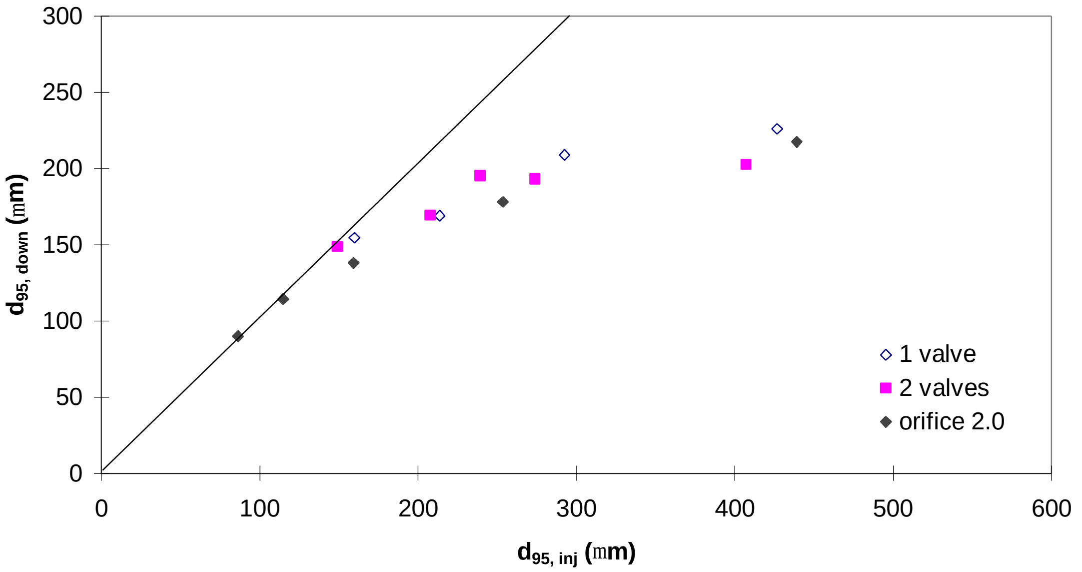

Figure 11: *Comparison of the break-up of oil droplets (Vitrea 46) in the 2.0 mm orifice, the needle valve and two valves in series. For all restrictions the flow rate is 1.45 l/min and the pressure drop 0.5 bar.*

the single valve. Consequently, the mean fluid velocity in the orifice of the valve decreases, and the residence time of the fluid in the turbulent zone inside the valve increases. The decrease in pressure drop and the increase in residence time of the fluid in the turbulent zone in the valve both contribute to the fact that the mean energy dissipation per unit time in the individual stages of the two valves in series is lower than the dissipation rate for the single valve. When droplets pass through the two valves, they interact with less intense turbulence than present in the single valve, and consequently the droplets remain larger in size than in case of the single valve.

The effect of the geometry of the restriction on the break-up process is not always as strong as shown in Fig. 10. The results obtained for the three types of restrictions under less severe conditions, i.e. a lower mean energy dissipation rate per unit mass, are shown in Fig. 11.

As can be observed in Fig. 11, the difference in droplet size downstream of the orifice, the valve and two valves in series is not as large anymore as shown in Fig. 10. Although it falls almost within the experimental error, which has been estimated to be 5 %, it can still be seen that on average the 2.0 mm orifice breaks up droplets to a slightly smaller diameter than the single valve does.

Analysis of the data obtained with the single valve and the two valves in series, show that there is hardly any difference in droplet diameters downstream of these restrictions. It has been argued before that the mean energy dissipation rate per unit mass in case of two valves in series is always smaller than for the single valve. Still the measurements show hardly any difference in droplet diameters. This phenomenon can be explained by considering that in case of two valves in series, a droplet has to travel through two turbulent zones. On one hand the mean energy dissipation rate per unit mass in each zone is low, resulting in less break-up. On the other hand, the residence time of droplets in the turbulent zones is increased, giving the turbulent eddies more opportunity to break up the droplets. In Fig. 10 the lowering of the mean energy dissipation rate per unit mass seems to be the dominant effect. In Fig. 11, however, this effect is counteracted by the increase in residence time of the droplets in the turbulent zones.

The break-up model, which has been described in the theory section, can be used to simulate the measurements shown in Figs. 10 and 11. Instead of comparing valves, the model compares a single orifice to two orifices in series. In order to achieve that the pressure drop across each individual orifice is equal to half the pressure drop across the single orifice, the following combinations have been used. An orifice of 1.0 mm has been compared to two orifices of 1.18 mm in series, and an orifice of 2.0 mm has been compared to two orifices of 2.31 mm in series. These combinations have been chosen bases on the orifice equation, which states that [16]:

$$\Delta p = \frac{1}{c_o^{\,2}} \frac{1}{2} r_c U_p^{\,2} \left(b^{-4} - 1 \right) \left(1 - b^2 \right) \qquad (12)$$

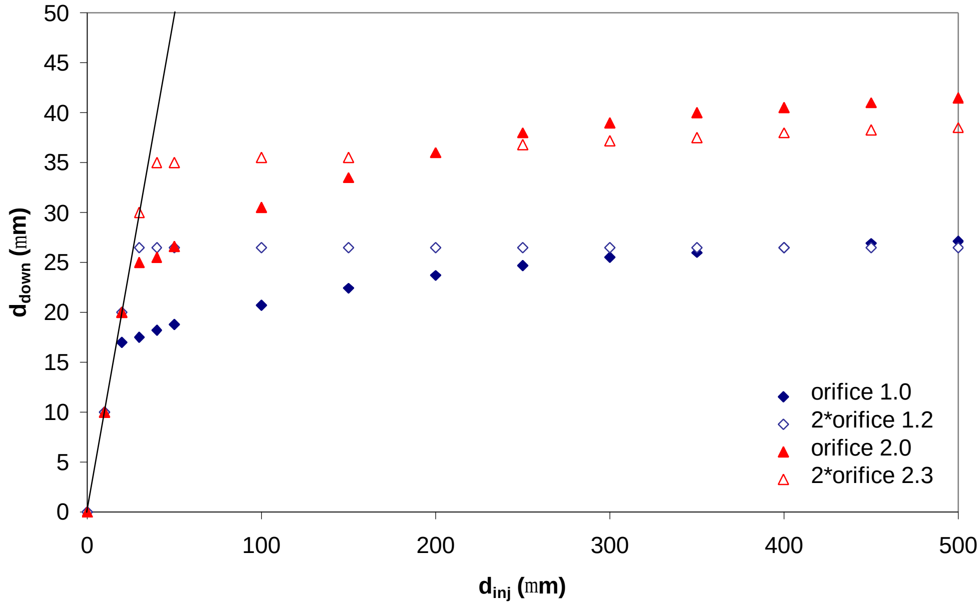

Figure 12: *Simulation of the break-up process as it takes place in a single orifice and two orifices in series. The flow rate through the 1.0 mm and the 1.18 mm orifices is 0.48 l/min, and through the 2.0 mm and 2.31 mm orifices 1.45 l/min. Vitrea 9 has been used as the dispersed phase.*

The value of the orifice coefficient, c_o, for sufficiently high Reynolds numbers is 0.62. For an identical flow rate, an orifice of 1.18 mm creates half the pressure drop a 1.0 mm orifice does. The same applies for an orifice of 2.31 mm and 2.0 mm. In Fig. 12 the simulations are shown.

The simulations plotted in Fig. 12 show a similar behaviour as the measurements in Figs. 10 and 11. For small droplets the two orifices in series cause less break-up than the single orifice. This is caused by the decrease in mean energy dissipation rate per unit mass. This beneficial effect is counteracted by the increased residence time of the droplets in turbulent zones. This last effect becomes more pronounced for large droplets since these droplets need to break up more times to reach the stable diameter. Normally large droplets do not stay long enough in the turbulent zone to reach d_{max}. The use of two orifices instead of one increases the residence time, which consequently leads to more break-up. Furthermore, it can be seen in Fig. 12 that the diameter at which the two effects balance shifts to lower values with decreasing turbulence intensity.

CONCLUSIONS

In case of turbulent break-up, the maximum stable droplet diameter downstream of an orifice can be predicted using the relation given in Eq. 3. An important parameter in the break-up process in the orifice is the mean energy dissipation rate per unit mass. In case of an orifice the relation given in Eq. 1 gives a good estimate of this dissipation rate.

Droplet sizes larger than the maximum stable droplet diameter can be observed downstream of the orifice. The explanation for this phenomenon is that in general not all droplets are allowed sufficient time inside the turbulent zone to break up to the maximum stable size. The theoretical beak-up model, which is described in this paper, is able to predict qualitatively the effect of the upstream droplet size on the size downstream of the orifice. This model incorporates the various time scales involved in the break-up process.

Experiments show that there is an effect of the geometry of the restriction on the droplet size downstream of a restriction. For a given flow rate and pressure drop, a needle valve causes less break-up than an orifice. This effect decreases with decreasing turbulence intensity.

Using two valves in series instead of one single valve can decrease break-up. Experiments show that this effect is most pronounced in case of intense turbulence. The theoretical break-up model shows that using two valves in series in stead of one single valve, only results in less break-up in case of a high mean energy dissipation rate per unit mass, and small droplets upstream of the restriction. For larger droplets the model predicts more break-up in case of two valves in series.

TECHNICAL CONTRIBUTIONS

In this paper a relation is provided to estimate droplet sizes downstream of an orifice. This relation can also be used to predict droplet sizes downstream of a choke valve. For this purpose, the mean energy dissipation rate per unit mass inside the choke valve has to be estimated. When the droplet-size distribution downstream of the choke valve is known, a suitable separator can be chosen to remove the oil from the water.

The droplet size downstream of the choke valve is sensitive to the geometry of the choke valve. Changing the choke valve can diminish break-up and, consequently increase the separation efficiency. Furthermore, using two choke valves in series can decrease break-up. In practice, this technique has proven to be useful for the decrease in sand erosion [17]. It should be noted, however, that two chokes in series could also cause extra break-up, which negatively effects the separation efficiency.

SYMBOLS

C: Constant [-]
D: Diameter [m]
Q: Volume flow rate [m^3/s]
T: Time [s]
U: Velocity [m/s]
V: Volume [m^3]
c: Constant [-]
d: Droplet diameter [m]
f: Volume fraction [-]
p: Pressure [Pa]
x: Distance [m]
Ω: Rate [s^{-1}]
β: Diameter ratio [-]
ε: Energy dissipation rate per unit mass [W/kg]
λ: Eddy size [m]
ρ: Density [kg/m^3]
σ: Interfacial tension [N/m]
τ: Stress [Pa]

Subscribts

95: 95 volume %
V: Volume
b: Break-up
c: Continuous phase
d: Dispersed phase
down: Downstream
inj: Injected
max: Maximum stable
min: Minimum
o: Orifice
p: Pipe
res: Residence
tot: Total

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