Experimental Study of Oil–Water Flow Downstream of a Restriction in a Horizontal Pipe

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Abstract: This work presents an experimental study on oil–water flow downstream of a restriction. The flow pattern, volumetric phase distribution, and their impacts on pressure drop are discussed. We employed two techniques to visualize the oil–water flow patterns, a high-speed camera and an Electrical Capacitance Volume Tomography (ECVT) system. The ECVT system is a non-intrusive device that measures the volumetric phase distribution at the pipe cross-section with time, which plays a critical role in determining the continuous phase in the oil–water flow, and therefore the oil–water flow pattern. In this study, we delved into the oil–water flow pattern and volumetric phase distribution for different valve openings, flow rates, and water cuts, and how they impact the pressure drop. The experimental results have demonstrated a strong relationship between the oil–water flow pattern and the pressure gradient, while the oil–water flow pattern is significantly influenced by the flowing conditions and the valve openings. The impacts of water cuts on the oil–water flow pattern are more obvious for smaller valve openings. For large valve openings, the oil and water phases tend to be more separated. This results in a moderate variation in the pressure gradient as a function of water cuts. However, it becomes more complex as the valve opening decreases. The pressure gradient generally increases with decreasing valve openings until the flow pattern becomes an oil-in-water dispersed flow. The impact of the valve on the pressure gradient is more pronounced in water-dominated flow when the water cut is above the inversion point, while it seems to be most obvious for medium water cut conditions.

Keywords: oil–water flow; flow pattern; electrical capacitance volume tomography; flow through restrictions; volumetric phase distribution; pressure gradient

1. Introduction

Oil–water two-phase flow widely exists in various industries. In the oil and gas industry, water production is becoming inevitable as the field matures. The oil–water flow pattern in pipes can significantly influence the pressure drop, which determines pipeline and wellbore design, pump selection and operation, and flow assurance. The behaviors of oil–water two-phase flow are less predictable compared to those of gas–liquid flow due to the similar physical properties and low interfacial shear stress between the two phases. It can be influenced by many factors, such as flow rates, pipe geometry, piping components such as elbows, reducers, multiphase flow meters, chokes or valves, etc.

Restrictions have ubiquitous applications in multi-phase flow pipelines in the oil and gas industry. Chokes are essential in adjusting a reasonable production rate for oil and gas wells to avoid an early water breakthrough into the wellbore [1]. They also help protect downstream equipment from high pressures to ensure safety in field operations [1]. However, the presence of valves can also cause other flow-assurance-related problems, such as the formation of stable emulsions in oil–water flow. The excessive mixing by the valves can disperse one phase into the other phase, and natural surfactants such as asphaltenes can stabilize the dispersions for a very long time, even forming tight emulsions. This can
cause extra demulsification costs to the fields. There are several studies in the literature investigating valve effects on droplet breakup mechanisms and downstream droplet sizes (Van der Zande et al., 1999; Malot et al., 2003; Dalmazzone et al., 2005; Fossen et al., 2006; Fossen and Schümann, 2016; Paolinelli and Yao, 2018; Silva et al., 2019) [2–8]. Yet, little attention has been paid to the effects of choke on downstream fluid behaviors such as flow patterns and their impacts on the pressure drop. Table A1 in the Appendix A summarizes the previous studies on the effects of restriction on oil–water flow for reference.

Choke can impact the downstream flow patterns and, consequently, the pressure gradient. Shmueli et al. (2019) observed that the oil–water flow pattern changed from stratified flow to dispersed flow under conditions of 0.2 bar pressure drop choking implemented near the inlet of their test section [9]. This alternation was verified by measuring water cut profiles at the pipe center in the vertical direction using a traversing narrow-beam gamma densitometer. A homogeneous water cut profile was observed for the 0.2 bar inlet mixing, while stratification was shown in the water volumetric fraction profile for the case without inlet choking. Schümann et al. (2016) [10] conducted experiments in a 25 m long horizontal pipe using a static mixer near the inlet of the test section. They compared the measured pressure drop at a distance of 200 pipe diameters downstream of the inlet mixer for cases with and without the mixer and concluded that there existed a substantial pressure increase for the water-dominated flow with the presence of an inlet mixer. By contrast, the pressure drop almost stayed constant for the oil-dominated flow with and without the mixer. However, none of these studies systematically examined how various choke sizes or openings impact the downstream flow behaviors.

The objectives of this study are to examine how various choke openings would impact the downstream flow pattern and volumetric phase distribution, and how they influence the pressure gradient. We employed two visualization methods to study the flow pattern: a high-speed camera that visualizes the flow pattern from the side and an Electrical Capacitance Volume Tomography (ECVT) system that sheds light on the phase volumetric distribution within the pipe. Their impacts on the pressure gradient are discussed afterward.

2. Materials and Methods

The experimental work was conducted in a three-phase flow loop at the Colorado School of Mines. This section introduces the experimental facilities, equipment, fluid properties, and the testing matrix used in this study.

2.1. Experimental Facilities

The flow loop in this study consists of a horizontal pipe with a length of 13.72 m and an inner diameter of 5.25 cm, as shown in Figure 1. The system was designed to introduce water and oil simultaneously through wye connections at the inlet. The experimental setup utilized a progressive cavity pump for the oil phase to minimize the shear effects and avoid the formation of tight emulsions. The oil flow rate was controlled by a frequency converter. A submersible pump was deployed to introduce water into the system, and the flow rate was manually controlled by a needle valve at the inlet. The oil and water flow rates were metered by two Coriolis flow meters (Emerson Micro Motion R100S) separately. The facility can also be used for three-phase flow study, and air can be introduced right after the wye-shaped oil connection. This study mainly focuses on oil–water two-phase flow.

To examine the effect of different choke openings on downstream flow behaviors, a 2 in. ball valve was installed immediately after the introduction of all phases. Pressure and temperature transducers were installed in the test section to monitor the pressures and temperatures. Two differential pressure transducers (Emerson Rosemount 3051S differential pressure transducer) were used to measure the pressure drops. One was installed across the ball valve and the other was set in the test section around 120 L/D (length/pipe inner diameter) downstream of the valve over a span of 5.5 m. The differential pressure sensors have a pressure range of −250 to 250 in H₂O with an accuracy of 0.025% of span. All the sensors were wired to a data acquisition system controlled by a LabView (2020) project,
which was used to automate the data acquisition and valve control to achieve the desired flow rates. The operational data were recorded at a time interval of 100 milliseconds.

Figure 1. The schematic of the flow loop.

2.2. Equipment for Flow Visualization

We employed two pieces of equipment to study the oil–water flow pattern in the pipe, a high-speed camera and an Electrical Capacitance Volume Tomography (ECVT) system (Tech4Imaging LLC, Columbus, OH, USA). Figure 2 shows a picture of the high-speed camera while running the experiments. It was placed in front of a clear acrylic pipe as shown in Figure 1.

Figure 2. A picture of the facility and the high-speed camera while running experiments.

The ECVT system was deployed downstream of the pressure drop measurement section to monitor the in situ volumetric phase distribution inside the pipe. It was clamped around the pipe and the system was calibrated with pure water and oil before actual measurements were taken. Pictures of the system are shown in Figure 3. The ECVT system was used in several previous studies, such as [11–13].

Figure 3. Pictures of the ECVT system and volumetric phase distribution at the pipe cross-section for 0% and 100% water cuts.

ECVT is a soft-field imaging modality in which a plurality of electrically conductive sensing plates are placed around a region of interest (RoI) [14]. Traditional ECVT utilizes 12, 24, or 36 rectangular electrodes configured around a cylindrical RoI. However, different numbers and shapes of plates can be configured around differently shaped RoIs including elbow, square, and spherical plates [15,16]. Twenty-four rectangular plates are used in this study with 4 rows of 6 plates in an offset configuration between rows.
The mutual capacitance is measured between all plate pairs surrounding the region such that, if there are a number of plates, \( N \), there are \( n \) mutual capacitance measurements created by \( n \) plate pairs as given by Equation (1) [14]. This excludes plates paired with themselves and duplicate plate pairs in which only the excite and detect functions of the plates are switched.

\[
n = \frac{N(N - 1)}{2}, \tag{1}
\]

There are two methods of measuring the mutual capacitance of each plate pair—alternating current (AC) and direct current (DC) [17]. In both cases, the measured signal is modulated by the permittivity of the mixture in between the plates. The AC version is used in this study. Lower permittivity corresponds to a lower signal and higher permittivity corresponds to a higher signal. Generally the capacitance, \( C \), between a parallel plate capacitor can be modeled according to Equation (2), where \( \varepsilon_0 \) is the permittivity of free space, \( \varepsilon_r \) is the relative permittivity of the dielectric, \( A \) is the area of the plate, and \( d \) is the distance between the two plates. While most of the plate pairs will not fall into the parallel plate category, the general principle is useful.

\[
C = \frac{\varepsilon_0 \varepsilon_r A}{d}, \tag{2}
\]

Typically, two phases are introduced into the sensing region and each capacitance measurement is normalized between the signal when the RoI is completely filled with each phase. The lower dielectric phase may be designated as the “empty” phase and normalized to 0 whereas the higher dielectric phase may be designated as the “full” phase and normalized to 1. Normalization is critical because each plate pair has its own biases due to the sensor geometry and variations in the data acquisition system channels. In this case, oil has \( \varepsilon_r \sim 2 \) and water has \( \varepsilon_r \sim 80 \) at room temperature.

Once the capacitance measurements are obtained, an image reconstruction algorithm must be used to generate the image from the data. A sensitivity matrix is used to map the capacitance data to the voxels (volumetric pixels) of the image. The number of voxels and size of the image can be determined by the user. In this study, a \( 20 \times 20 \times 20 \) voxel image is used. These voxels are vectorized into an \( 8000 \times 1 \) vector, \( g \). The vector, \( c \), contains the capacitance measurements and is \( 276 \times 1 \). The sensitivity matrix, \( S \), is therefore \( 276 \times 8000 \) and contains the sensitivity or weight of each capacitance measurement to each voxel in the image. The forward problem is, therefore,

\[
c = Sg \tag{3}
\]

This problem is both ill-conditioned and ill-posed and there are many proposed solutions. In this study, we used LBP. \( S \) is typically generated in a multi-physics simulation, \( c \) is measured, and \( g \) is solved for through solving the inverse problem. For more details on related topics, please see [18,19].

Our initial tests with pure oil or water alone flowing in the pipe showed reasonable results, as indicated in the right plots in Figure 3. The pure oil is indicated in blue, whereas the pure water is shown in red. In dispersed flow, the red color should denote a water-continuous state while the blue or yellow color indicates an oil-continuous state. In the experimental results, we will show the volumetric phase distribution variation with time inside the pipe in the axial direction at the center of the pipe, and at the pipe cross-section at different times.

2.3. Fluid Properties and Text Matrix

Tap water was used as the aqueous phase and mineral oil (Isopar V) as the oil phase. The oil density is 810 kg/m\(^3\) and viscosity is 14.6 mPa·s at 20 °C and atmospheric pressure. The interfacial tension (IFT) between the oil and tap water was measured by a Krüss tensiometer DSA 100 using the pendant drop method. The measured IFT demonstrated a
transient behavior and stabilized at 40 mN/m after 5 min. More data on the IFT between Isopar V and tap water can be found in [20]. The oil density and viscosity were measured by an Anton Paar SVM 3001 Stabinger Viscometer at various temperatures. A linear relationship was established for density as a function of temperature, and a logarithmic relationship was obtained for viscosity. Those equations were used for estimating the in situ oil density and viscosity at the different temperatures experienced in the test section during the experiments.

Table 1 lists the testing matrix of this study. Five valve openings, seven water cuts, and two mixture velocities were studied. Each flowing condition was stabilized for at least 10 min before measurement started.

### Table 1. Testing matrix.

<table>
<thead>
<tr>
<th>Mixture Velocity $v_M$</th>
<th>Water Cut WC</th>
<th>Valve Opening</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 m/s</td>
<td>20%, 60%, 80%</td>
<td>100%, 75%, 50%, 30%, 20%</td>
</tr>
<tr>
<td>0.5 m/s</td>
<td>60%</td>
<td>100%, 75%, 50%, 30%, 20%</td>
</tr>
<tr>
<td>0.2 m/s</td>
<td>0%, 20%, 30% $^3$, 40%, 60%, 80%, 100%</td>
<td>100%, 50%, 30%</td>
</tr>
<tr>
<td>0.5 m/s</td>
<td>0%, 20%, 30% $^3$, 40%, 60%, 80%, 100%</td>
<td>100%, 75%, 50%, 30%</td>
</tr>
</tbody>
</table>

$^1$ Mixture velocity is the total velocity of oil and water. Mathematically, it is the total volumetric flow rate of oil and water divided by the pipe’s cross-sectional area. $^2$ Water cut is defined as the volumetric fraction of water in the injected liquid stream. Mathematically, it is the superficial water velocity (water volumetric flow rate divided by the pipe’s cross-sectional area) divided by the mixture velocity. $^3$ The 30% water cut was only investigated for certain valve openings.

### 3. Results

In this section, we first discuss the flow pattern generally observed in this study, followed by two subsections that discuss the impacts of valve opening and water cuts, respectively, on the flow pattern, volumetric phase distribution, and pressure gradient.

#### 3.1. Flow Patterns

Figure 4 shows the flow patterns observed in the current study. The pictures on the left were taken from the high-speed camera videos. The axial plots in the middle are the volumetric phase distribution with time at the center of the pipe obtained from the ECVT system, while the cross-sectional plots on the right show the volumetric phase distribution in the pipe at different time frames also obtained from the ECVT system. The red color represents water, and the blue is oil. The ECVT data were recorded at a frequency of 41.73 Hz.

Overall, seven major flow patterns were observed in the current study, including stratified flow with a mixing interface (ST&MI), a free oil layer above a water-in-oil dispersed layer (O&W/O), a water-in-oil dispersed layer above a free water layer (W/O&W), a water-in-oil dispersed layer above an oil-in-water dispersed layer (W/O&O/W), an oil-in-water dispersed layer above a free water layer (O/W&W), oil-in-water dispersion (O/W), and water-in-oil dispersion (W/O).

The ST&MI flow pattern is one of the most observed flow patterns in this study. It mainly occurs when there are low flow rates, large valve openings, and medium water cut conditions. O&W/O flow mainly occurs under conditions of high liquid flow or when there are small valve openings with low water cut conditions. Occasionally, there is a sub-flow pattern in O&W/O, in which rolling waves made of large water droplets are present above the interface. A picture of it is shown in Figure 4. W/O&W flow normally occurs at high water cut conditions. Under certain rare flow conditions, small oil slugs were observed at the top part of the pipe. This type of flow pattern should be around the transition but is classified as W/O&W considering the relatively small size of oil pockets observed in this study. W/O&O/W, which is also referred to as dual dispersion or dual continuous flow by some previous studies [21–26], occurs at medium water cut and high flow rate or small valve opening conditions. O/W&W flow occurs at high water cut, small valve opening, or high liquid flow rate conditions. Occasionally, random W/O slugs appear...
within O/W&W flow at the top port of the pipe under some flowing conditions, which is clearly shown in the ECVT images. O/W flow occurs at small valve openings at medium or high water cut conditions. W/O flow occurs at low water cut, small valve opening, and high flow rate conditions. The next section discusses in detail the flow pattern transition with different valve openings, liquid mixture velocities, and water cuts. Flow pattern maps are presented together with the pressure gradient plots to enhance the understanding of their correlations. It is also worth noting that the flow pattern transitions in a gradual manner, resulting in some fluctuation or intermittency, which is shown clearly in the ECVT images. Understanding this phenomenon aids in comprehending its impacts on the pressure gradient, which are discussed in the next section.

Figure 4. Oil–water two-phase flow patterns observed in this study. (Left): high-speed camera video pictures; (middle): volumetric phase distribution at the center of the pipe in the axial direction obtained from ECVT; (right): volumetric phase distribution at the cross-section of the pipe at three different times obtained from ECVT).

3.2. Effect of Valve Opening on Flow Pattern and Pressure Gradient

The changes in downstream flow behavior with valve openings are illustrated by a series of experiments with a mixture velocity of 0.2 m/s at 20%, 60%, and 80% water cuts, and a mixture velocity of 0.5 m/s at 60% water cut. As anticipated, the valve plays a critical role in determining the oil–water flow patterns. Our experimental data also demonstrated that the oil–water flow pattern impacts the corresponding pressure gradient dramatically.

Figure 5 shows the flow patterns at different valve openings when the input water cut is 20%. The pictures on the left were captured by the high-speed camera. The images in the middle demonstrate the volumetric phase distribution in the vertical direction at the pipe center as a function of time, obtained from the ECVT system. The square images on the right are the volumetric phase distributions at the cross-section of the pipe at three different time frames, also obtained from the ECVT system. The percentages shown on the left are the valve openings. As shown by Figure 5, the flow pattern for 100% to 50% valve openings is ST&MI based on the high-speed camera videos, with an increase in mixing
at the interface as the valve opening is reduced. Transition to O&W/O flow occurs when the valve opening decreases to 30%. Some rolling waves made of large water droplets were observed occasionally above the interface. They grow as the valve opening is further reduced, indicating transitioning to W/O.

Figure 5. Flow pattern observed from the high-speed camera (left) and variation of volumetric phase distribution at the pipe center in the vertical direction (middle) and volumetric phase distribution at the pipe’s cross-section at three different time frames (right). \( v_{SL} = 0.2 \text{ m/s} \) with a 20% water cut (the percentages in the picture indicate the opening of the valve).

The corresponding pressure gradient measurement is shown as a green line in Figure 6, with a flow pattern indicated for each testing point. For a 20% water cut, the pressure gradient shows a little increase as the valve opening decreases from 100% to 50%, when the flow pattern remains ST&MI. This increase could be due to the increasing mixing at the oil and water interface that leads to a higher frictional pressure drop. As the flow pattern transitions to O&W/O when the valve opening reduces to 30% and 20%, the pressure gradient starts to show a noticeable increase with decreasing valve opening, which is due to the increase in mixture viscosity in the bottom dispersed layer. For a better understanding of the flow pattern transition, Figure 7 provides a flow pattern map using coordinates of water cut and valve opening.

Figure 8 shows the flow pattern and the volumetric phase fraction in the axial and cross-sectional planes for a 60% water cut at the same liquid mixture velocity (0.2 m/s). It can be seen that the flow pattern remains ST&MI for valve openings \( \leq 50\% \), but with more mixing at the interface and a thicker water layer compared to that for the 20% water cut. The flow pattern transitions to O/W&W as the valve opening is reduced to 30%. Some small W/O slugs appear intermittently at the top part of the pipe, which is shown more clearly in the ECVT images. We anticipate that this point could be near the transition boundaries. The upper part of the fluid flow could generate high frictional pressure losses due to the densely packed dispersed O/W and W/O flows [10], leading to a peak in the pressure gradient plot shown in Figure 6 (black line). As the valve opening is reduced to 20%, the flow pattern starts to transition to O/W flow, where W/O slugs are occasionally present at the pipe top as illustrated from the ECVT axial plot. This leads to a decrease in the pressure drop when the valve opening is reduced from 30% to 20%.
Figure 6. Pressure gradient in the test section as a function of valve opening at 0.2 m/s liquid mixture velocity and different water cuts.

Figure 7. Flow pattern map for 0.2 m/s total mixture velocity as a function of valve opening in the x-axis and water cut in the y-axis.

Figure 8. Flow pattern observed from the high-speed camera (left) and variation of volumetric phase distribution at the pipe center in the vertical direction (middle) and volumetric phase distribution at the pipe’s cross-section at three different time frames (right). $v_{SL} = 0.2$ m/s with a 60% water cut (the percentages in the picture indicate the opening of the valve).

A similar flow pattern transition occurs for cases with an 80% water cut as for a 60% water cut, but with a much thicker mixing layer. Figure 9 shows the flow pattern and the
volumetric phase fraction in the axial and cross-sectional planes for an 80% water cut at the same liquid mixture velocity (0.2 m/s). ST&MI flow was observed for valve openings of 100% and 75%, although the oil layer at the top of the pipe was very thin. Transition to W/O&W starts at a valve opening of 50%, earlier than for the 60% water cut where the transition occurred at a valve opening of around 30%. The flow pattern starts to change to O/W flow when the valve opening is further decreased. For the 30% valve opening, we suspect that the top layer contains intermittent W/O and O/W dispersed flows as illustrated in the ECVT images in the axial direction. The corresponding pressure gradient measurement is shown in Figure 6 (orange line). Similar trends were observed for 80% and 60% water cuts, i.e., the pressure gradient increases as the valve opening is reduced until the flow becomes dispersed oil in water.

![Figure 8](image1)

**Figure 8.** Flow pattern observed from the high-speed camera (left) and variation of volumetric phase distribution at the pipe center in the vertical direction (middle) and volumetric phase distribution at the pipe’s cross-section at three different time frames (right). $v_{SL} = 0.2$ m/s with an 80% water cut (the percentages in the picture indicate the opening of the valve).

Another interesting observation from Figure 6 is that the valve’s impact on the pressure gradient is more obvious for water-dominated flow than oil-dominated flow (note that the inversion point is between a water cut of 20% to 30% for our testing fluids). In our experiments, the valve impact is most obvious for a 60% water cut, while it is less noticeable for a 20% water cut.

The effect of choking on flow pattern and pressure gradient was also investigated at a higher liquid mixture velocity. Figure 10 shows the corresponding pictures from the high-speed camera and the images from the ECVT system for a mixture velocity of 0.5 m/s. When compared with Figure 8, one can notice that the transition from ST&MI flow to the other flow patterns starts earlier at a valve opening of 50%, whereas this transition occurred at a valve opening of 30% when the mixture velocity was 0.2 m/s. The elevated mixture velocity shifts the flow pattern transition to a larger valve opening.

For the 50% valve opening, we think the flow pattern was O/W&W, but with some small W/O pockets in the upper parts based on the ECVT axial image. The upper part should still be dominated by O/W. The viscosity of this upper densely packed dispersed flow could be high even though it is water-continuous, which eventually leads to the peak in the pressure gradient plots shown in Figure 11. This is consistent with Schümann et al. (2016)’s results, who observed similar phenomena for a liquid mixture velocity of 0.5 m/s at water cuts of 50% and 80%, and first described the top layer as a densely packed water-continuous layer [27]. They used quick-closing valves to observe the separation of the top layer, from which they concluded that the top layer should be oil droplets in the water phase.
we emphasize the water cut’s effect on the flow pattern, phase distribution, and pressure pattern observations. However, the oil droplets are still a little bit concentrated towards the cut, which enhances the dispersion of water droplets into the upper oil layer. The thickness could be induced by the increased superat the interface and a thicker free water layer as expected. The increased mixing layer all water cuts from 20% to 80%. An increase in the water cut leads to a thicker mixing layer

Figure 10. Flow pattern observed from the high-speed camera (left) and variation of volumetric phase distribution at the pipe center in the vertical direction (middle) and volumetric phase distribution at the pipe’s cross-section at three different time frames (right). \(v_{SL} = 0.5\) m/s with a 60% water cut (the percentages in the picture indicate the opening of the valve).

![Image of flow pattern](image)

Figure 11. Pressure gradient in the test section as a function of valve opening at 0.5 m/s liquid mixture velocity and 60% water cut.

When the valve opening is reduced to 30%, the flow pattern becomes O/W, demonstrated by both the high-speed camera videos and the ECVT images. The pressure gradient drops abruptly as the valve opening decreases from 50% to 30%, consistent with our flow pattern observations. However, the oil droplets are still a little bit concentrated towards the top of the pipe due to buoyancy for the 30% valve opening, as illustrated from the ECVT images. The flow becomes more homogeneous as the valve opening is reduced to 20%, resulting in an even smaller pressure gradient.

### 3.3. Effect of Water Cut on Flow Pattern and Pressure Gradient

As indicated in the previous section, the oil–water flow pattern, volumetric phase distribution, and pressure gradient are also closely related to the water cut. In this section, we emphasize the water cut’s effect on the flow pattern, phase distribution, and pressure gradient in the test section downstream of the inlet valve. The effect of the water cut is investigated at two different mixture velocities and four different valve openings.

Figure 12 shows the flow pattern and phase distribution for different water cuts at 0.2 m/s mixture velocity and a valve opening of 100%. ST&MI was generally observed for all water cuts from 20% to 80%. An increase in the water cut leads to a thicker mixing
layer at the interface and a thicker free water layer as expected. The increased mixing layer thickness could be induced by the increased superficial water velocity at a higher water cut, which enhances the dispersion of water droplets into the upper oil layer.

Figure 11. Pressure gradient in the test section as a function of the water cut at 0.2 m/s liquid mixture velocity and different valve openings.

The black line in Figure 13 shows the corresponding pressure drop as a function of the water cut, with the flow pattern noted on the side. Figure 14 shows the corresponding flow pattern map in terms of water cut on the x-axis and valve opening on the y-axis. The pressure gradient first decreases slightly when the water cut changes from 0% to 20% due to the addition of the free water layer that has a lower viscosity than the oil phase. Then it increases until the water cut reaches 80%. This is mainly due to the increase in the thickness of the mixing layer, which has a higher viscosity. Although the free water layer also grows as the water cut increases, their negative impact on the pressure gradient is outweighed by the positive and larger impact from the mixing layer.

The impacts of the water cut on the oil–water flow pattern are more obvious for smaller valve openings. Figure 15 shows the flow pattern and phase distribution for a valve opening of 50% at the same mixture velocity. The corresponding pressure gradient measurement is shown as a green line in Figure 13. The flow pattern is ST&MI for water cuts ≤ 60%, and transitions to W/O&W at an 80% water cut, at which the pressure gradient reaches the maximum. Oil slugs are occasionally present at an 80% water cut, which are captured by the high-speed video camera. The variation in pressure gradient with varying water cuts is consistent with the flow pattern observations.

![Figure 12](image-url) Flow pattern observed from the high-speed camera (left) and variation of volumetric phase distribution at the pipe center in the vertical direction (middle) and volumetric phase distribution at the pipe’s cross-section at three different time frames (right). \( v_{SL} = 0.2 \text{ m/s with a 100\% valve opening (the percentages in the picture indicate the water cut).} \\

![Figure 13](image-url) Pressure gradient in the test section as a function of the water cut at 0.2 m/s liquid mixture velocity and different valve openings.
100% and 50%, respectively. The corresponding pressure gradients as functions of the water cuts are shown in Figure 19, and the flow pattern is shown in Figure 20. It can be observed that the pressure gradient and the water cut for a valve opening of 50% at 0.5 m/s is similar to the flow pattern observed from the high-speed camera. The variation in pressure gradient with varying water cuts is consistent with the flow pattern observations.

Figure 14. Flow map for 0.2 m/s total mixture velocity as a function of the water cut on the x-axis and valve opening on the y-axis.

Figure 15. Flow pattern observed from the high-speed camera (left) and variation of volumetric phase distribution at the pipe center in the vertical direction (middle) and volumetric phase distribution at the pipe’s cross-section at three different time frames (right). \( v_{SL} = 0.2 \text{ m/s} \) with a 50% valve opening (the percentages in the picture indicate the water cut).

Figure 16 shows the fluid flow behavior for a valve opening of 30%. O&W/O was observed under 20% water cut conditions, W/O&W for 30% and 40% water cut conditions, and O/W&W for 60% and 80% water cut conditions, which is also indicated in Figures 13 and 14. Since W/O dispersion has a higher mixture viscosity than O/W dispersion for the same type of fluids, the pressure gradient is at its maximum at around the 30% and 40% water cuts (red line in Figure 13). Figure 13 clearly shows that the pressure gradient of oil–water two-phase flow is strongly impacted by water cut and flow pattern, and the latter could be influenced significantly by pipe restrictions.

Similar behavior was observed for a higher mixture velocity of 0.5 m/s. Figures 17 and 18 show the flow patterns and phase distributions for valve openings of 100% and 50%, respectively. The corresponding pressure gradients as functions of the water cuts are shown in Figure 19, and the flow pattern is shown in Figure 20. It can be noticed that the flow tends to be more mixed at the higher mixture velocity, resulting in flow pattern transitions occurring at smaller water cuts. The relationship between the pressure gradient and the water cut for a valve opening of 50% at 0.5 m/s is similar to...
that of a valve opening of 30% at 0.2 m/s. At 0.5 m/s, when the valve opening is 30%, the fluid flow is dispersed flow for all water cuts, with an inversion point between the 20% and 30% water cuts. This phenomenon is reflected in the ECVT images (Figure 21) and the pressure gradient measurements shown in Figure 19, which show a peak at around the 30% water cut.

**Figure 16.** Flow pattern observed from the high-speed camera (left) and variation of volumetric phase distribution at the pipe center in the vertical direction (middle) and volumetric phase distribution at the pipe’s cross-section at three different time frames (right). $v_{SL} = 0.2 \text{ m/s}$ with a 30% valve opening (the percentages in the picture indicate the water cut).

**Figure 17.** Flow pattern observed from the high-speed camera (left) and variation of volumetric phase distribution at the pipe center in the vertical direction (middle) and volumetric phase distribution at the pipe’s cross-section at three different time frames (right). $v_{SL} = 0.5 \text{ m/s}$ with a 100% valve opening (the percentages in the picture indicate the water cut).
Figure 18. Flow pattern observed from the high-speed camera (left) and variation of volumetric phase distribution at the pipe center in the vertical direction (middle) and volumetric phase distribution at the pipe's cross-section at three different time frames (right). $v_{SL} = 0.5 \text{ m/s}$ with a 50% valve opening (the percentages in the picture indicate the water cut).

Figure 19. Pressure gradient in the test section as a function of water cut at 0.5 m/s liquid mixture velocity and different valve openings. (Note: the flow patterns in black color are for both 100% and 75% valve openings).

Figure 20. Flow pattern map for 0.5 m/s total mixture velocity as a function of the water cut on the $x$-axis and valve opening on the $y$-axis.
we have a better understanding of the phase distributions, especially the continuous dispersed flows such as O/W&W, W/O&W, O/W, and W/O. However, ECVT also has some limitations. It has low accuracy at the phase interface near the pipe wall; low detectability of large water droplets in the oil phase, such as the ones in ST&MI and W/O&W flows; and low detectability of the oil phase volumetric fraction in water-continuous dispersed flow. Therefore, we recommend using both a high-speed camera and the ECVT system for a better understanding of the flow behavior for future studies.

4. Discussion

Oil–water flow is widely encountered in various industries. In this study, we emphasized the oil–water flow pattern downstream of restrictions, and their impacts on the pressure drop, which is a crucial factor in production system design and optimization, flow assurance, etc. [1]. For fluids containing natural surfactants, the restriction effect is more pronounced because these surfactants stabilize the formed droplets and prevent their coalescence. In other words, restriction effects on multiphase flow can persist over very long distances when natural surfactants are present. Additionally, understanding the distribution of oil and water phases downstream of a restriction is crucial for gas hydrate prediction and management. Besides pressure and temperature, gas hydrate formation depends on the interfacial area between different phases, which is a function of the flow pattern and phase distribution. Restrictions induce significant turbulence to the fluid flow, enhancing phase mixing and consequently affecting the interfacial area and gas hydrate formation. Furthermore, accurately predicting the pressure drop in surface flow lines, which involve numerous flowline components and chokes, is crucial for flow allocation assessment using hydraulic models. For the first time, this study provides a systematic study of the effects of restrictions on oil–water flow patterns, volumetric phase distribution in the axial and cross-sectional directions, and the pressure gradient.

We employed two visualization methods, a high-speed camera and an ECVT system, to better understand the behavior of oil–water fluid flow. The high-speed camera videos were recorded on the side of the horizontal pipe, which provided limited information on the fluid flow behavior within the pipe. By combining these videos with the ECVT system, we have a better understanding of the phase distributions, especially the continuous phase in dispersed flows such as O/W&W, W/O&W, O/W, and W/O. However, ECVT also has some limitations. It has low accuracy at the phase interface near the pipe wall; low detectability of large water droplets in the oil phase, such as the ones in ST&MI and W/O&W flows; and low detectability of the oil phase volumetric fraction in water-continuous dispersed flow. Therefore, we recommend using both a high-speed camera and the ECVT system for a better understanding of the flow behavior for future studies.
Although the hydraulic modeling work on oil–water flow has been ongoing for decades, the restriction effects are still not well-captured. Our next goal is to develop a mechanistic model for oil–water flow in horizontal pipes that considers the effects of restriction, water cut, and flow rate on the pressure gradient.

5. Conclusions

An experimental study was conducted in this study to investigate the oil–water flow behavior downstream of restrictions in a horizontal pipe, and their impact on the pressure gradient. We employed two visualization methods to study the flow patterns, a high-speed camera that visualizes the flow pattern from the side and an Electrical Capacitance Volume Tomography (ECVT) system that sheds light on the volumetric phase distribution within the pipe.

Seven oil–water flow patterns were observed in this study, namely stratified flow with a mixing interface (ST&MI), a free oil layer with a dispersed water-in-oil layer (O&W/O), a dispersed water-in-oil layer with a free water layer (W/O&W), a dispersed water-in-oil layer with a dispersed oil-in-water layer (W/O&O/W), a dispersed oil-in-water layer with a free water layer (O/W&W), dispersed water-in-oil (W/O), and dispersed oil-in-water (O/W).

The experimental results have demonstrated a strong relationship between the oil–water flow pattern and the pressure gradient, while the oil–water flow pattern is significantly influenced by the flowing conditions and the valve openings. The impacts of water cuts on the oil–water flow pattern are more obvious for smaller valve openings. For large valve openings, the oil and water phases tend to be more separated and the flow pattern tends to be ST&MI at medium water cuts or low mixture velocities, and the droplets are generally large. This results in a moderate variation in the pressure gradient as a function of water cut. However, it becomes more complex as the valve opening decreases. The pressure gradient generally reaches the maximum when W/O&O/W flow occurs. On the other hand, the pressure gradient increases with decreasing valve openings until the flow pattern becomes O/W flow. The impact of the valve on the pressure gradient is more pronounced in water-dominated flow when the water cut is above the inversion point, while it seems to be most obvious for medium water cut conditions.

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Conflicts of Interest: Authors Benjamin Straiton and Qussai Marashdeh were employed by the company Tech4Imaging. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1 in this appendix summarizes the previous experimental studies of oil–water flows downstream of restrictions.
### Table A1. Experimental studies of oil–water flows downstream of restrictions.

<table>
<thead>
<tr>
<th>Authors</th>
<th>Restriction Type</th>
<th>ID (mm)</th>
<th>( \Theta^* ) (°)</th>
<th>Flow Rate Range (m/s)</th>
<th>Fluids</th>
<th>Properties</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>van der Zande et al.</td>
<td>Orifice</td>
<td>4.5, 15.25</td>
<td>-</td>
<td>0.5–5.5</td>
<td>n-heptane, Vitrea 9, 46, 68; tap water and demineralized water</td>
<td>( \mu_o = 0.4–410 \text{ cP}; \rho_o = 684–882 \text{ kg/m}^3 )</td>
<td>Drop breakup</td>
</tr>
<tr>
<td>Malot et al. (2003)</td>
<td>Orifice</td>
<td>4.8</td>
<td>90</td>
<td>0.46–0.92</td>
<td>crude oil; brine</td>
<td>( \mu_o = 10.6 \text{ cP}; \rho_o = 847 \text{ kg/m}^3 )</td>
<td>Drop breakup, droplet size</td>
</tr>
<tr>
<td>Dalmazzone et al. (2005)</td>
<td>Orifice</td>
<td>30</td>
<td>90</td>
<td>0.007</td>
<td>Heptane; tap water</td>
<td>( \mu_o = 0.45 \text{ cP}; \rho_o = 684 \text{ kg/m}^3 )</td>
<td>Drop breakup, droplet size</td>
</tr>
<tr>
<td>Fossen et al. (2006)</td>
<td>Needle valve</td>
<td>6.35</td>
<td>0</td>
<td>0.263</td>
<td>Exxsol D60; 3.5 wt.% NaCl</td>
<td>( \rho_o = 780 \text{ kg/m}^3 )</td>
<td>Droplet size</td>
</tr>
<tr>
<td>Schümann et al. (2016)</td>
<td>Static mixer</td>
<td>100</td>
<td>0</td>
<td>0.5–1</td>
<td>Primol 352 + Exxsol D80; tap water</td>
<td>( \mu_o = 35–120 \text{ cP}; \rho_o = 853–866 \text{ kg/m}^3 )</td>
<td>Flow pattern, phase distribution, pressure drop, droplet size</td>
</tr>
<tr>
<td>Fossen and Schümann</td>
<td>Butterfly valve</td>
<td>100</td>
<td>0</td>
<td>0.18–0.71</td>
<td>Primol 352 + Exxsol D60; tap water + NaOH</td>
<td>( \mu_o = 4 \text{ cP}; \rho_o = 800 \text{ kg/m}^3 )</td>
<td>Droplet size</td>
</tr>
<tr>
<td>Paolinelli and Yao (2018)</td>
<td>Globe valve</td>
<td>100</td>
<td>0</td>
<td>1.1–1.6</td>
<td>Isopar V; 0.1 wt.% NaCl</td>
<td>( \mu_o = 9 \text{ cP}; \rho_o = 810 \text{ kg/m}^3 )</td>
<td>Droplet size</td>
</tr>
<tr>
<td>Shmueli et al. (2019)</td>
<td>Ball valve</td>
<td>69</td>
<td>0</td>
<td>0.5–2</td>
<td>Exxsol D80; tap water</td>
<td>( \mu_o = 1.8 \text{ cP}; \rho_o = 803 \text{ kg/m}^3 )</td>
<td>Flow pattern, water distribution, pressure drop</td>
</tr>
<tr>
<td>Silva et al. (2019)</td>
<td>Gate valve</td>
<td>12.7</td>
<td>-</td>
<td>4.52–4.49</td>
<td>Mineral oil; tap water</td>
<td>( \mu_o = 12, 26 \text{ cP}; \rho_o = 865.6 \text{ kg/m}^3 )</td>
<td>Droplet size</td>
</tr>
<tr>
<td>Skjefstad et al. (2020)</td>
<td>Ball valve</td>
<td>67.8</td>
<td>0</td>
<td>1.38–2.31</td>
<td>Exxsol D60; 3.2 wt.% NaCl</td>
<td>( \mu_o = 1.6 \text{ cP}; \rho_o = 795.74 \text{ kg/m}^3 )</td>
<td>Separation performance</td>
</tr>
</tbody>
</table>

* Inclination angle from horizontal, 90° is upward vertical, 0° is horizontal, - is not available.

**References**


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