Flow rate measurement of oil-water two-phase flow based on V-cone flow meter

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Abstract. In petroleum industry, oil-water two-phase flow widely exists in production wells, and the measurement of oil-water flow is significant in oil well logging. One method in common use is to build a theoretic model to connect differential pressures generated by a throttling set with flow-rate. Several measuring models were adopted and compared for model selection and modification. A V-cone with 0.65 diameter ratio was selected as the throttling set because of its special structure and intrinsic advantages. In the experiments, the differential pressures measured under different flow range were processed with a homogeneous flow model. And the results show that the error is small in the condition where the oil and water are well mixed, while the error is big when they are not well mixed. A polynomial of the error and the water percentage was fitted to improve the model accuracy and widen the measurement range.

1. INTRODUCTION
In the measurement of oil-water two phase flow, one method that is commonly used is getting flow rate information from the pressure drop of fluid flows. This measuring method in oil-water two flow field is usually sumarized as one measuring model which is called pressure drop model. And pressure drop model includes stratified flow model and homogeneous flow model. The basic idea of the separated model is to treat the two phases separately as a single fluid. Each phase is assumed to flow alone in the pipe with its own flow parameters and properties. Homogeneous flow model is the condition that water and oil mixes so well that the mixture can be seen as one single phase approximately. Unlike gas-water two phase flow, each phase of oil-water two phase flow has the similar flow characteristics. So the measuring model that suits for gas-water two phase flow can not be used in oil-water two phase flow. Charles (1961) was a earlier researcher who worked on the oil-water two phase flow regime. He laid some foundations for oil-water two phase flow. In 1980s, Arirachakaran (1989) did some experiments about stratified flow, mixed flow, annular flow, intermittent flow and homogeneous flow. And they came to the conclusion that take oil phase as one kind of high density “gas phase”, the flow regime were much similar. Several years later, Hewitt (1997) studied and compared the flow regime of oil-water two phase flow and gas-water two phase flow, and concluded that stratified flow exists in both of the two kinds of two phase flow; though slug flow is very common in gas-water two phase, it is very rare in oil-water two phase flow; in gas water two phase flow, only as the gas percentage is less than 30% gas phase could disperse into water phase, but water phase never disperse into gas phase, while in the oil-water two phase flow, each can disperse into the other phase no matter what the phase percentage is; annular flow is a typical and common
flow regime in gas-water two phase flow, but in oil-water two phase flow annular flow is hardly appeared. During this period, Nadler (1995) also reported some much similar conclusions. Trallero (1996) summarized the method about flow regime of oil-water two phase flow and that is widely used so far.

\[
\begin{align*}
\text{Stratified} & \quad \{ \text{ST} \} \\
& \quad \{ \text{ST} \ & \text{MI} \} \\
\text{Homogeneous} & \quad \{ \text{Water} \} \\
& \quad \{ \text{Do/w} \ \& \ \text{w} \} \\
& \quad \{ \text{w/o} \} \\
& \quad \{ \text{Oil} \} \\
& \quad \{ \text{Do/w} \ \& \ \text{Do/w} \} \\
\end{align*}
\]

The throttling set is one of the primary elements used in the flow-rate measurement by introducing pressure drop. When fluid passes the throttling set, the cross section area of the fluid decreases, then the velocity of the fluid increases. Consequently the pressure difference between the upstream and downstream of the throttling set results in the differential pressure which represents the flow-rate of the fluid.

For the advantages of high reliability and accuracy, simple structure as well as easy installation, the throttling sets have gained wide applications in single phase flow measurement and in broad investigation on two-phase flow rate measurement. In the middle of 1980s, came out a new kind of V-cone flow meter, which is shown in Figure 1. The streamlined structure of V-cone overcomes the disadvantages of other throttling sets that can be easily jammed due to the high viscosity of oil flows. The noise signal created by the fluid flows through the V-cone is much lower than that generated by other throttling sets (Sun, 2004).

As the fluid flows through the V-Cone meter, the differential pressure \(\Delta P\) is generated from the shrinking area of the cross-section. With a wider measurement scale, it is more accurate and effective in flow rate measurement, for which, V-cone becomes a popular research field for two-phase flow measurement.

2. MEASUREMENT METHOD OF FLOW-RATE ON OIL-WATER TWO PHASE FLOW

Previous researchers had worked on the flow regime of the oil-water two phase flows, but their achievements never refer to the relationship of the flow rate and the flow regimes. However, the flow regime factor is very important for flow rate measurement of oil-water two phase flows. It also determines the measuring model adopted.

When the mixture of water and oil passes the V-cone, according to the Bernoulli equation

\[
\frac{p_1}{\rho_1} + \frac{u_1^2}{2} = \frac{p_2}{\rho_2} + \frac{u_2^2}{2} \tag{1}
\]
And the fluid continuity equation:

$$A_1u_1 = A_2u_2$$  \hspace{1cm} (2)

$p_1, p_2, u_1, u_2, \rho_1, \rho_2, A_1, A_2$ represent the upstream pressure of V-cone, the downstream pressure of V-cone, upstream flow-rate, downstream flow-rate, upstream fluid density, downstream fluid density, upstream circulation area, downstream circulation area respectively. If the fluid is incompressible, then $\rho_1 = \rho_2 = \rho$, $A_2 = \mu A_0$, where $A_0$ is the circulation area of the V-cone, thus

$$u_2 = \frac{1}{\sqrt{1 - \mu^2}} \sqrt{\frac{2}{\rho} (p_1 - p_2)} \hspace{1cm} (3)$$

and $\mu^2 = \beta^4$, $\beta$ is the equivalent diameter ratio. Because $p_1$ and $p_2$ are average pressures, the modified formula $\frac{\sqrt{p_1 - p_2}}{\sqrt{p_1 - p_2}} = \sqrt{\psi}$ is necessary, where $\sqrt{\psi}$ is called pressure tapping coefficient which changes as the mode of the pressure tapping changes. Introducing $\varepsilon$ to modify the $u_2$ (considering the loss due to fluid viscosity), so

$$u_2 = \varepsilon u_2 = -\varepsilon \sqrt{\psi} \sqrt{\frac{2}{\rho} (p_1 - p_2)} \hspace{1cm} (4)$$

The volume flow-rate is

$$q_v = u_2 \mu A_0 = \frac{\mu \varepsilon \sqrt{\psi}}{\sqrt{1 - \beta^4}} A_0 \sqrt{\frac{2}{\rho} \Delta p} \hspace{1cm} (5)$$

Discharge coefficient is defined: $C = \mu \varepsilon \sqrt{\psi}$, then

$$q_v = \frac{Ce}{\sqrt{1 - \beta^4}} A_0 \sqrt{2 \Delta p \rho} \hspace{1cm} (6)$$

For $A_0 = \frac{\pi}{4} (D^2 - d^2)$ $D$ is the diameter of pipe, $d$ is the largest cross section area of V-cone, so the mass flow-rate is determined by:

$$q_m = \frac{Ce}{\sqrt{1 - \beta^4}} \frac{\pi}{4} (D^2 - d^2) \sqrt{2 \Delta p \rho} \hspace{1cm} (7)$$

Consider oil-water two-phase flow as one single kind of fluid, the density of the fluid $\rho_m$ is expressed as
\[
\frac{1}{\rho_w} = \frac{\omega_o}{\rho_o} + \frac{1 - \omega_o}{\rho_w} \quad (8)
\]

\(\omega_o\) is mass fraction of oil, \(\rho_o\) is the density of oil phase, \(\rho_w\) is the density of the water phase. In fact, the density of the oil-water flow should be modified with parameter \(n\). Substitute equation (8) into equation (7), we get

\[
G = \frac{CA}{\sqrt{(1 - \beta^2)}} \sqrt{2\Delta p\rho_w/[1 + (\frac{\rho_w}{\rho_o} - 1)\omega_o^n]} \quad (9)
\]

\(G\) is the mass flow-rate of oil-water two-phase flow, and \(n\) represents the situation of oil-water flow. And the more mixture mixed, the more \(n\) close to unity (Ma et al., 2007).

The relationship between mass fraction of oil \(\omega_o\) and volume fraction of water \(\phi_w\) is

\[
\omega_o = [1 + \frac{\rho_w}{\rho_o}(\frac{1}{1 - \phi_w} - 1)]^{-1} \quad (10)
\]

So

\[
G = \frac{CA}{\sqrt{(1 - \beta^2)}} K \sqrt{2\Delta p\rho_w} \quad (11)
\]

\(K\) is modified coefficient of oil-water two-phase flow based on V-cone.

\[
K = \left\{1 + \frac{\rho_w}{\rho_o}(\frac{1}{1 - \phi_w} - 1)\right\}^{-\frac{1}{2}} \quad (12)
\]

Thus, mass flow rate of oil and water are

\[
G_o = G/[1 + \frac{\rho_w}{\rho_o}(\frac{1}{1 - \phi_w} - 1)] \quad (13)
\]

\[
G_w = G - G_o \quad (14)
\]

3. EXPERIMENT AND RESULTS

The test section is a Perspex pipe in a stainless horizontal pipe loop. The diameter of the pipe is 50mm. The Oil-water loop contains an oil-water separation tank, an oil tank, a water tank, a V-cone flow meter, an industrial control computer, several vortex flow meters, and several pumps and valves. The industrial control computer controls the opening degree of the valves in order to control the flow rate of oil phase and water phase. The flow range of water and oil in this work is about: 0 - 12 \(m^3/h\) and 0 - 50 \(m^3/h\) respectively. The density of the oil is 841.7 \(kg/m^3\), and its viscosity is around 14.3 cp. As the mixture of water and oil flows through the V-cone flow meter with a diameter ratio of 0.65 for this work, there will be a certain differential pressure between the upstream and the downstream of V-cone flow meter. Thus groups of differential pressure are obtained with the flow rate of oil-water two phase.
flow changes. At last, the mixture of water and oil flows into the oil-water tank for separation, then the oil and water are pumped to oil tank and water tank separately.

![Flow Diagram](image)

**Fig. 2 Oil-water two phase flow loop**

The V-cone meters are not standard flow meters, so they must be calibrated before experiments. The parameter that needs calibration is Discharge coefficient $C$. Ten groups of water experiments were conducted to calculate this parameter, as shown in Figure 3 that all the data points are stabilized around 0.8-0.9. An average value of 0.83 was used in the models adopted.

![Discharge Coefficient vs Renold's Number](image)

**Fig. 3 Calibration of Discharge Coefficient**

The procedure of the experiments is: in one experiment data set, water flow rate is fixed; then gradually increase the oil flow rate until reach the maximum; change the water flow rate to a bigger value, increase the oil in the same way to get next data set. The results of the experiments are shown in Figure 4:
where the error is defined as $\varepsilon = \frac{G_{a} - G}{G_{a}}$, and $G_{a}$ is actual flow rate, $G$ is the flow rate which is calculated through the measuring model.

When the oil-water two phase flow was in stratified flow, the measuring error was very big with the maximum error reached 40%. As the mixing degree increasing so that the oil-water two phase flow was in transitional flow, then the measuring error decreased a little but it was still too high to suit for the measurement. When the oil and water were well mixed that the oil-water two phase flow was approximately considered as one single phase, i.e. homogeneous flow condition, thus the error reduces to less than 10%.

In order to make the measuring model fit for a wider scale and improve the measuring accuracy, a certain modification is needed when the oil-water two phase flow is in stratified flow or transitional flow. And the repeatability of oil-water two phase flows when they are in homogeneous flow needs to be verified.

The basic idea of the first task is, when an oil-water two phase flow is in stratified flow or transitional flow, a relationship that is about error $\varepsilon$ and its determinant will be determined and a correlation will be fitted. As known that the mixing degree is a decisive factor that affects the measuring error, while water percentage $\phi_{w}$ determines the mixing degree. Consequently, error $\varepsilon$ is of the relation with water percentage $\phi_{w}$. Thus, from the definition of error, the actual flow rate can be expressed as $G_{a} = \frac{G}{1-\varepsilon}$.

On the condition that the oil-water two phase flows were in stratified flow, a polynomial about error $\varepsilon$ and water percentage $\phi_{w}$ was fitted:

$$\varepsilon = -0.1226\phi_{w}^{-1} + 0.0975\phi_{w}^{2} - 0.0943\phi_{w} + 0.3421 \quad (15)$$

When it was in stratified flow, applied equation (15) into $G_{a} = \frac{G}{1-\varepsilon}$ and found that the error was significantly reduced, as shown in Figure 5.

With the same method, a polynomial about error $\varepsilon$ and water percentage $\phi_{w}$ was fitted when the oil-water two phase flow was in transitional flow, as expressed by equation (16).

$$\varepsilon = -0.7092\phi_{w}^{-1} + 0.9688\phi_{w}^{2} - 0.3895\phi_{w} + 0.3847 \quad (16)$$

The comparison results showed that the error decreased significantly as well. As shown in Figure 6, the calculated flow rate is very close to the actual flow rate. Thus the results based on the modified
measuring model are meaningful under the condition that the oil-water two phase flow is in stratified flow or transitional flow.

As discussed above, when the oil and water are well mixed, the error of measurement based on the model reduced. In order to make sure that the measuring model is repeatable for the measurement, this research involved many groups of repetitive experiments. By changing the ratio of water and oil, the results of homogeneous flow experiments and repetitive experiments are shown in Figure 7.

Obviously, under the similar conditions, the results of repetitive experiments are very close to the results of original experiments. The experimental results show that in oil-water two-phase flows, the measuring model adopted in this work can only be used in homogeneous flow regime unless it is modified. And the modification varies with flow regime. For verification, the experimental results are compared with the increasing water flow rate and with different oil fraction range. The results are seen in Figure 8.

The three groups of conditions in this work are oil percentage is bigger than 50%, oil percentage is bigger than 20% and smaller than 50%, oil percentage is smaller than 20%. As the flow rate of water phase increases, the measurement error based on the measuring model is decreasing. And the higher the flow rate of water is, the better the oil-water two phase flow mixed. So the experiments also show that the measuring model without modification is only suitable for the homogeneous flow, and when the oil-water two phase flow is stratified flow or transitional flow the modification is necessary.

In addition, when water and oil mixture flows in low flow rate, they tend to flow separately and usually are treated as two separate fluids flow alone, and the separate models rather than homogeneous models would be more appropriate in that case.
4. CONCLUSIONS

From a series of experiments of oil-water two-phase flows in a 50mm diameter Perspex horizontal pipe, the flow rates were measured with a V-cone flow meter with 0.65 diameter ratio. A measuring model is presented and proved efficient when the oil-water two phase flows are in homogeneous flow through repetitive experiments. However, the error of the measuring model grows beyond the acceptable limit, when oil-water mixtures were in stratified flow or transitional flow. In order to make the measuring model suitable for a wider scale and better accuracy, a certain modification is carried.
out. From the analysis that the factor which affects the measuring accuracy is the mixing degree of the oil and water, the modification correlation was established. The results show that the measurement accuracy was improved by the modified correlations. These experiments and results suggest that the better the oil and water mix, the lower the measuring error would be.

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NOMENCLATURE

| Symbol | Description                      | Units   |
|--------|----------------------------------|---------|
| $p$    | pressure                         | [Pa]    |
| $u$    | flow velocity                    | [m/s]   |
| $A$    | circulation area                 | [m$^2$] |
| $D$    | diameter of pipe                 | [m]     |
| $S$    | the largest cross section area of V-cone | [m$^2$] |
| $q$    | flow-rate                        | [m$^3$/s] |
| $C$    | discharge coefficient            |         |
| $n$    | mixing degree coefficient        |         |
| $K$    | modified coefficient of oil-water two-phase flow based on V-cone |         |

Greek Letters

| Symbol | Description                      | Units   |
|--------|----------------------------------|---------|
| $\rho$ | fluid density                    | [kg/ m$^3$] |
| $\beta$ | equivalent diameter ratio |         |
| $\psi$ | pressure tapping coefficient |         |
| $\varepsilon$ | error |         |

Subscripts

| Symbol | Description                      |
|--------|----------------------------------|
| 1      | upstream                         |
| 2      | downstream                       |
| 0      | V-cone flow meter                |
| o      | oil                              |
| w      | water                            |
\[ v \quad \text{volume} \]
\[ m \quad \text{mass} \]
\[ \quad \text{absolute value} \]

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