Study of water-oil mixture separation in bottomhole area via drift flow model

E M Almukhametova, A A Karimova, F F Almukhametov, N Kh Gabdrakhmanov, A Kh Gabzalilova and Z A Garifullina

1Oktyabrsky Branch of Ufa State Petroleum Technological University, 54a, Devonskaja Street, Oktyabrskii, Republic of Bashkortostan, 452607, Russia
2NGDU “Tuymazaneft”, Kuvykina 32, Oktyabrskii, Republic of Bashkortostan, 452607, Russia

E-mail: elikaza@mail.ru

Abstract. The existing methods to study the movement and pattern of flow in wells with electric submersible pump (ESP) within the ‘bottomhole-pump-wellhead’ system are rather experimental and empirical. Hence, the lack of universal techniques considering all possible operating modes of wells does not allow using the existing techniques to elaborate the measures improving the efficiency of well operation with ESP. Besides, these techniques cannot always be applied to define the optimum operating modes and to determine the need for various well intervention jobs as they are not quite perfect. The improvement of profitability of well operation is intimately connected with deliberate change of flow properties and structure considering various physical properties of fluids and ESP-based operating modes with further formation of fine emulsions. In this regard, the modern petroleum industry is facing an urgent task to study the processes in a bottomhole and a wellbore zones using a generalized mathematical model with further analysis of various perturbing actions on emulsion stability, assessment of its decrease and separation of the water phase within subsurface equipment.

1. Introduction

It is typical to study the movement of multicomponent mixture in ascending pipes via the ‘drift’ flow [1]. This model assumes the relative speed of light (oil) phase due to the difference in flux density. At the same time one phase (heavy) moves upwards as a continuous medium, while the other comes to the surface as drops of a discontinuous phase.

The model of a drift flow covers the multidirectionality of phase movements. The most complex one is the counter flow of fluids when the heavy phase (water) moves down and the light one up. Such fluxes are characterized by the so-called ‘flooding’, i.e. carryover of a light phase by the downward movement of a heavy phase, or, on the contrary, carryover of a heavy phase by the upward flow of a light phase.

For a flooded well this may happen in case when the oil interlayer is placed between a water suction pump and a water interlayer.

Thus, there is a probability of failure of separate oil and water withdrawal from different levels when the water-saturated interlayer is located above the oil-saturated one. The oncoming movement of oil and water, especially at high speeds, may disturb the flows, i.e. water can carry the oil phase down and vice versa. In hydrodynamics of vertical flows this phenomenon is studied by H. Wallis [2].
Earlier it was obtained that the production rate limit of oil \( Q_o \) and water \( Q_w \) in the oncoming movement when the flow is ‘flooded’ in the Arlansky oil field demonstrates the following values (Table 1).

| \( Q_o \), m³/day | 31.2 | 20.8 | 14.0 | 8.64 | 5.09 | 2.94 |
|-------------------|------|------|------|------|------|------|
| \( Q_w \), m³/day | 0    | 12.7 | 25.4 | 31.8 | 50.8 | 63.5 |

Within a large group of wells of the Arlansky field the density of extracted fluid was analyzed by running the gamma density meter to the borehole bottom through the annular space [4,6]. It was established that the fluid density is jumping at the level of the suction pump (Figure 1). There is a column of dry crude oil above the suction pump and a water column below it where the extracted oil gets from a bottomhole to a pump in the form of single globules.

The structure of water-oil mixture at the bottomhole provides for simultaneous and sequential withdrawal of oil and water from different levels [5,7,8]. At the same time, oil and water are withdrawn using one tail piece lowered by a bottom end to a rathole.

The withdrawal of fluid only, for example, water will lead to gradual accumulation of oil in space between a casing string and a tailpiece. Once the level of ‘oil-water’ separation reaches a point of water withdrawal, the flow changeover takes places and oil is pumped from the top intake. At the same time, the water intake is blocked and initiates the gradual rise of the oil-water level. After this level reaches the top intake, the flow changeover shall take place with further dewatering. Then the cycle is repeated.

The connection of a tailpiece with the suction pump allows pumping oil and water out in sequence without mixing them. It shall be noted that today there is no equipment for gradual pumping of oil and water out of wells equipped with ESP.

In view of the fact that the majority of statistical information is used for conditions of the Tuymazinsky field, the author measured the fluid density at bottomhole sites of some wells within this field to define the maximum speed of oil and water in counter flows in case of their successive withdrawal.

In [10] the authors describe the ratio of drift flow density calculated as the density of oil volume flow rate through the surface moving with the speed of a mixture:

\[
W_f = W_c (\varphi - W),
\]

where \( \varphi \) – true content of water in a mixture; \( W \) – consumption water content; \( W_c = Q_c/S \) – specific speed of a mixture in a casing string; \( Q_c \) – fluid flow rate; \( S \) – cross-section of a column.

\( \varphi \) is defined by a measured flow density in a column under known density of oil and water:

\[
\varphi = (\rho_f - \rho_o) / (\rho_w - \rho_o)
\]

It is more advisable to present the formula (1) as equations of straight lines in coordinates \( W_1 \) and \( W_2 \):

\[
W_1 = (1 - \varphi) / \varphi, \quad W_2 = W_1 + \varphi
\]

where \( W_1 \) and \( W_2 \) – specific speed for oil and water (\( W_1 = Q_o/S \); \( W_2 = Q_w/S \)). To define \( \varphi \) the fluid density \( \rho_f \) was defined by a downhole pressure gauge lowered below the suction pump to the perforation interval. The analysis was performed for three wells. The mean density on some site of a well depth was defined by the following expression:

\[
\rho_{mf} = (P_1 - P_2)/g(L_1 - L_2),
\]

\( P_1, P_2 \) – pressures at depths \( L_1 \) and \( L_2, \) N/m².

2. Materials and methods

The issues raised in the given work were solved through the theoretical study of the mechanism of fluid flow structure formation within the ‘bottomhole-pump-wellhead’ system, analysis and generalization of field data on ESP-based operations, measurement of bottomhole and wellbore
pressure, study of oil emulsion stability at the wellhead and in water collection and separation pipelines.

3. Results

Graphic construction of a flooding line of formation fluid in counter flows of oil and water.

To obtain a full curve of flow flooding in case of oncoming movement of oil and water the [10] refer to the method developed by H. Wallis, i.e. an envelope on a series of straight lines (2, 3) in the 4th quadrant of a diagram, i.e. at positive $W_1$ and negative $W_2$ (Figure 1).

![Figure 1. Dependence of $W_1$ on $W_2$ in Tuymazinsky field at $(1 - \varphi)$: 1 – 0.035; 2 – 0.15; 3 – 0.34; 4 – flooding line.](image)

This causes the need for an experiment to measure $\rho_f$ for a quite large group of wells with different water content. Besides, they shall mainly cover the greatest water content interval of wells. Such dependences are related to high costs of field studies caused by running of subsurface equipment.

This section is devoted to the technique of receiving the fluid flooding conditions in a counter flow of oil and water using fluid density at the bottomhole of only three wells for the purpose of obtaining a stable mean value. The technique shows that the speed of a relative movement of an oil phase in the upward flow of continuous medium (water) is accepted as a constant for this field, i.e. for similar density of oil and water for each deposit or field.

It is easy to get the expression for a relative speed of a light phase in a drift flow for the following reasons. Let us set the values of oil ($Q_o$) and water ($Q_w$) flowrate, cross-sections of production string $S$ as well as cross-sections occupied with oil ($S_o$) and water ($S_w$). Besides, the well flowrate $Q_f$ and water $W$ are also set. From the definition:

$$U = \frac{Q_o/S_o - Q_w/S_w}{\varphi - W}$$  \hspace{1cm} (5)

considering that $Q_0 = Q_f - Q_w$, $\varphi = S_w/S$, and $W = Q_w/Q_c$, is easy to obtain the expression [8,10]:

$$U = \frac{(\varphi - W)}{\varphi (1 - \varphi)} \cdot W_c$$  \hspace{1cm} (6)

$\varphi$ differs from $W$ since the true content of oil in the specified pipeline volume is less the consumable due to the relative speed.

Having the speed $U$ obtained according to the minimum quantity of wells and accepting it as a constant for a given deposit, from (6) it is possible to receive a formula to calculate $\varphi$ based on the known values $U$, $W_c$, $W$ (quadratic equation):

$$\varphi = (U - W_c) + \frac{\sqrt{(W_c - U)^2 + 4UWB_c}}{2U}$$  \hspace{1cm} (7)

In (7) the minus before a discriminant shall not be considered due to the negative value $\varphi$ that contradicts the physical meaning.
Thus, having set $Q_o$, $W$ and $U$ it is possible to receive any direct dependence (3) for the given oil deposit. The legitimacy of this technique, namely, considering $U$ as a constant for a deposit or a field may be illustrated according to data obtained by the author in work on the Arlansky field. In this work the authors $\varphi$ and $W_c$ at known $W$, $Q_o$, $U$, $S$ for 39 wells. The author added Table 2 with the column No. 8 illustrating the relative speed $U$.

The average $U$ value for all groups of wells made $5.3 \times 10^{-2} \text{ m/s}$ with the reliability $R_c = 0.98$, i.e. close to a unit. Therefore, for another deposit with a sufficient accuracy it is advisable to measure the fluid density at the bottomhole of 3 wells only and then calculate $U$.

For Tuymazinsky oil field the relative speed $U$ makes $5.50 \times 10^{-2} \text{ m/s}$.

Figure 1 shows the lines built for some wells in $W_1 - W_2$ coordinates. The curved line touching the lines in the 4th quadrant allows receiving the flooding conditions of oil and water in fluid counter flows.

**Table 2. Experimental and design data of drift flows**

| Well | $Q_o$, m$^3$/day | $Q_w$, m$^3$/day | $W$ | $\rho_w$, kg/m$^3$ | $\varphi$ | $W_c$, $10^2$ m/s | $U$, $10^2$ m/s |
|------|------------------|-----------------|-----|-------------------|---------|-----------------|-----------------|
| 38   | 5.4              | 21.6            | 0.8 | 1140              | 0.93    | 2.12            | 4.23            |
| 599  | 2.8              | 5.2             | 0.65| 1148              | 0.96    | 0.63            | 5.09            |
| 608  | 12.3             | 17.7            | 0.59| 1120              | 0.86    | 2.36            | 5.29            |
| 609  | 3.6              | 4.4             | 0.55| 1148              | 0.96    | 0.63            | 6.73            |
| 611  | 9.75             | 5.25            | 0.35| 1130              | 0.91    | 1.18            | 8.07            |
| 622  | 8.93             | 10.07           | 0.53| 1126              | 0.88    | 1.5             | 4.97            |
| 625  | 1.15             | 3.85            | 0.77| 1157              | 0.99    | 0.39            | 8.67            |
| 640  | 1.2              | 7.8             | 0.8 | 1157              | 0.99    | 0.71            |                 |
| 730  | 7.2              | 4.8             | 0.4 | 1140              | 0.93    | 0.94            | 7.65            |
| 980  | 3.12             | 4.88            | 0.61| 1145              | 0.95    | 0.63            | 4.51            |
| 1000 | 13.5             | 13.5            | 0.5 | 1123              | 0.87    | 2.12            | 6.94            |
| 1018 | 3.6              | 5.4             | 0.6 | 1145              | 0.95    | 0.71            | 5.23            |
| 1019 | 4.5              | 14.4            | 0.76| 1145              | 0.95    | 1.49            | 5.96            |
| 1049 | 2.5              | 3.36            | 0.57| 1151              | 0.97    | 0.46            | 6.32            |
| 1047 | 6                | 24              | 0.8 | 1145              | 0.95    | 2.36            | 7.45            |
| 1154 | 7.7              | 14.3            | 0.65| 1140              | 0.93    | 1.73            | 7.44            |
| 1166 | 9.4              | 21.9            | 0.7 | 1130              | 0.91    | 2.46            | 6.31            |
| 1167 | 21.2             | 10.6            | 0.5 | 1103              | 0.8     | 2.5             | 4.69            |
| 1191 | 1.72             | 2.28            | 0.57| 1151              | 0.97    | 0.31            | 4.26            |
| 1199 | 6.5              | 6.5             | 0.5 | 1145              | 0.95    | 1.02            | 9.66            |
| 1271 | 9.46             | 12.54           | 0.57| 1140              | 0.93    | 1.73            | 9.57            |
| 1331 | 14.3             | 11.7            | 0.45| 1120              | 0.86    | 2.05            | 6.98            |
| 1379 | 10.8             | 9.2             | 0.46| 1126              | 0.88    | 1.57            | 6.24            |
| 1395 | 28.5             | 21.5            | 0.43| 1083              | 0.73    | 3.93            | 5.98            |
| 1441 | 2.6              | 1.4             | 0.35| 1145              | 0.95    | 0.31            | 3.92            |
| 1456 | 2.4              | 5.6             | 0.7 | 1154              | 0.98    | 0.63            | 9.00            |
| 1472 | 2                | 2               | 0.5 | 1154              | 0.98    | 0.31            | 7.59            |
| 1477 | 1.2              | 1.8             | 0.6 | 1155              | 0.98    | 0.24            | 4.65            |
| 1478 | 2.9              | 4.8             | 0.62| 1156              | 0.97    | 0.6             | 7.22            |
| 1579 | 12.5             | 9.46            | 0.43| 1117              | 0.85    | 1.73            | 5.70            |
| 1580 | 7.15             | 3.85            | 0.35| 1131              | 0.9     | 0.86            | 5.26            |
| 2019 | 5.8              | 4.2             | 0.42| 1143              | 0.94    | 0.79            | 7.28            |
| 2219 | 5                | 8.9             | 0.64| 1145              | 0.95    | 1               | 6.53            |
| 2562 | 4.6              | 6.4             | 0.53| 1151              | 0.97    | 0.86            |                 |
| 2598 | 7.68             | 8.32            | 0.52| 1137              | 0.92    | 1.26            | 6.85            |
| 6103 | 18               | 11              | 0.38| 1111              | 0.83    | 2.28            | 7.27            |
| 7236 | 3.71             | 3.29            | 0.47| 1145              | 0.95    | 0.55            | 5.56            |
| 7555 | 2.56             | 5.44            | 0.68| 1151              | 0.97    | 0.63            | 6.28            |
| 7949 | 12.5             | 16.5            | 0.57| 1123              | 0.87    | 2.28            | 6.05            |
4. Conclusions

The experience of ESP-based operation of wells shows that pumped-out fluid, correlation of phases, viscosity of phases, gaseous phase has a considerable impact on pump characteristics.

There are different views and interpretations of the formation of fluid density in a bottomhole zone and the presence of a relative speed within a two-phase system, however there is no unambiguous opinion on the mechanism of flux movement in laminar and turbulent modes. Therefore, in order to increase the efficiency of ESP-based operation of wells, there is a need to specify the mechanism of formation and movement of water-oil mixtures from a bottomhole to a wellbore using the mathematical model and to study the influence of water-oil emulsions on pump characteristics.

References
[1] Fletcher K 1991 Computing Methods in Fluid Dynamics (Moscow: Mir) pp. 552
[2] Patankar S 1984 Numerical Methods of Heat Exchange and Fluid Dynamics ed V D Vilensky (Moscow: ENERGOATOMIZDAT)
[3] Marsden S S and Raghavan R 1988 Canadian ship bitumen by pipe-line. Oil and Gas J. 86(21)
[4] Patankar S 1980 Numerical heat transfer and fluid flow (New York: Himisphere Publishing Corporation)
[5] Simon R 1968 Downhole emulsification in oil well. J.Petrol.Technology 20(12) 1349-1353
[6] Mukhametshin V V 2017 Eliminating uncertainties in solving bottom hole zone stimulation tasks. Bulletin of the Tomsk Polytechnic Univ. Geo Assets Eng. [in Russian – Izvestiya Tomskogo Politehnicheskogo Universiteta] 328(7) 40-50
[7] Almukhametova E M, Gizetdinov I A, Kilmamatova E T, Akimov A V, Kalinina S V and Fatkullin I F 2017 Use of precipitate formation technology to increase oil recovery under Tarasovskoye field conditions. IOP Conf. Ser.: Earth Envir. Sci. (87)052001
[8] Almukhametova E M, Akimov A V, Kalinina S V, Fatkullin I F and Gizetdinov I A 2017 Efficiency of preliminary discharge of stratum water in Tuymazinskoe oil field. IOP Conf. Ser. Earth Envir. Sci. 87(6) 062001
[9] Srivastova R and Narasinimarty G 1973 Hydrodynamics of non newtonial two-phase flow in pipes. Chem. Eng. Sc. 28(2) 553-558
[10] Wilcox D C 1994 Turbulence modeling for CFD (DCW Industries Inc.) pp 460