Investigation of pump-ejector systems characteristics for water alternating gas injection

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ABSTRACT: In this article, the experiments conducted to increase the efficiency of the use of pumping-ejector systems used for the enhanced oil recovery method. This method is the water alternating gas injection. Water alternating gas injection implies the injection of alternately water and gas, or a water-gas mixture - simultaneous water alternating gas. The purpose of these experiments is to study the jet apparatus characteristics at high pressures at the ejector's intake (0-0.3 MPa), as well as to develop a new calculation methodology for the rheometer. Studies were conducted on a laboratory bench, allowing research at various gas flow rates. The article presents new dependencies for the three possible stand designs that allow recalculation of gas flow. The new rheometer calculation methodology can reduce the inaccuracy from 20% to 1.8%. The results of experiments that, the maximum value of the ejector efficiency is equal to 32.5%, and the injection rate varies from 1 - 1.14, under these experiments conditions.

Keywords: pump-ejector systems, characteristic of liquid-gas ejector, water alternating gas injection

1 INTRODUCTION

Simultaneous water alternating gas (SWAG) injection is a combination of conventional water-flooding and gas injection techniques. Unlike water, which takes up small hydrophilic pores and bottlenecks in the flooded zone of the reservoir, pumped gas as a non-wetting phase takes large hydrophobic pores, and the top of the reservoir under the action of gravitational forces (Drozdov et al. 2006). These aspects of oil displacement have led to reasonability of maintaining reservoir pressure by water and gas injection. At the same time, the displacement profile is also aligned, and the formation coverage is increased. Various authors carried out laboratory filtration experiments on the displacement of oil and hydrocarbon liquids from the reservoir by water, gas and various combinations of these agents. The results of experiments (Piyakov et al. 1992) on the use of water alternating gas (WAG) injection showed that the

injection of gas and water, regardless of the type of gas used and the stage of flooding, contributes to an increase in the displacement efficiency. The value of the increase of displacement efficiency is a function of the gas agent composition. The minimum increase of 7-8% was obtained in experiments using nitrogen; upon injection of dry hydrocarbon gas, the increase was 15-16%; with an increase in the content of intermediate components C_2-C_4 in a hydrocarbon gas, the displacement efficiency increased. The series of experiments on core samples (Fatemi et al. 2013), taking into account the wettability of the reservoirs, proves the effectiveness of the use of WAG compared to injecting water or gas separately.

Experiments (Stepanova 2003) suggested that the most significant effect of WAG was observed for media with mixed wettability, when hydrophobic surfaces form through paths along large pores, while smaller ones remain hydrophilic. The direct observation of physical processes occurring in a porous medium during WAG was carried out on the water-wet glass micromodel (Sohrabi et al. 2000). Various water alternating gas technologies over the past decades have been applied at almost a hundred fields in the world, both abroad and in our country. The successful ratio of using WAG according to data in foreign practice exceeds 90% (Berge 2002).

With the simultaneous injection of water and gas, the greatest effect according to the data (Egorov 2006, Liskevich 1973, Drozdov 2006) is achieved when the gas content of the water-gas mixture is in the range of 25-75%. Now abroad, dry or enriched hydrocarbon gases, as well as carbon dioxide, are usually injected into WAG technologies. The most commonly reported increase in oil recovery during WAG is approximately 5%, but, as noted in some fields, oil recovery may increase by 20%. Studies (Lei et al. 2016) have shown the efficiency of WAG CO_2 for multilayer formation.

In the article (Christensen et al. 2001) extensive review of the WAG injection process has been presented. The increase in oil production of the considered fields is about 5-10%. To obtain the effect of WAG and to avoid early breakthrough of the injection gas, it is necessary to have a good idea of the phase of the behavior of the reservoir oil and injection gas mixtures, as well as the heterogeneity of the reservoir.

The experimental study of WAG and SWAG injection schemes with CO_2 (Kamali 2017) is aimed at determining the function of co-optimization function for CO_2 storage and incremental oil production. Experiments are run to represent immiscible, near-miscible, and miscible displacements. Numerical simulations show a remarkable reduction in gas relative permeability for the WAG and SWAG displacements compared with continuous-gas-injection displacements, as a result of which the vertical-sweep efficiency of CO_2 is improved.

A comprehensive review of WAG field displacements and their effect on oil recovery and produced-gas/water ratio has been presented in the literature (Stalkup 1983; Christensen et al. 2001).

The vast simulation study (Nygård & Andersen 2020) has been performed investigating immiscible WAG injection focusing on mechanisms such as mobility, gravity, injected volume fractions, reservoir heterogeneity, gas entrapment, and relative permeability hysteresis.

Scientists (Hoare & Coll 2018, Kumar et al. 2017, Khorsandi et al. 2017; Alzayer & Sohrabi 2018) note the influence of hysteresis relative permeability on the effectiveness of WAG. It is often expected that the gas phase will show large hysteresis effects (Hoseini et al. 2011). Hysteresis lowers gas mobility and hence improves the gas/oil mobility ratio and reduces gravity segregation. The first effect is always positive, but the second is mainly positive in more uniform reservoirs where gravity segregation has a negative effect on recovery. In heterogeneous reservoirs, reducing gravity segregation can lead to the oil in low-permeability layers remaining unswept. (Nygård & Andersen 2020)

Most foreign fields with WAG technologies are located in Canada, the USA and Norway (Skauge & Stensen 2003, Christensen et al. 2001, Cone 1970, Quale et al. 2000, Righi & Pascual 2007, Shi et al. 2008, Stoisits et al. 1995, Choudhary et al. 2011, Gbadamosi et al. 2018, Olalotiti-Lawal et al. 2018).

In Russia, experimental work on the WAG was carried out at the Sovetskoye and Vakhskoye (Kryuchkov 2002), Ilishevskoye (Shuvalov et al. 2008), Alekseevskoye (Vafin 2008, Zaripov 2006), Novogodnee (Zakirov et al. 2006), Vostochno-Perevalnoye (Zatsepin & Chernikov 2007, Chubanov et al. 2008) and at the Sredne-Hulymyskoye fields (Chubanov et al. 2008).

In foreign practice, complex and expensive equipment that requires large capital investments, high-quality maintenance and competent operation – gas treatment units, pumps and high pressure compressors – is used to implement gas and water exposure. Attempts to apply the WAG compressor technology at the Samotlorskoye and Novogodnoye fields under Russian conditions, despite the enormous costs, were ultimately discontinued.

So the traditional technology of SWAG injection is not widely used in domestic oil fields. The main problem is the absence of effective processes and technologies for water and gas pumping into injection wells. In this situation, the use of jet technology, in particular pump-ejector systems, may turn out to be a very attractive solution.

In previously published papers (Krasilnikov 2010, Drozdov et al. 2008), laboratory studies of pump-ejector systems were carried out at constant pressure at the jet apparatus intake P_{in} (0; 0.5 MPa) with different values of relative power pressure drop created in the ejectors working nozzle ΔP_p . In this article, the characteristics of an ejector with a constant ΔP_p with a relative outlet pressure drop ΔP_o created by a jet apparatus were considered.

2 PURPOSE

The purpose of this work is to characterize the pump-ejector system at high pressures at the jet apparatus intake within 0 – 0.3 MPa. Additionally, the differential pressure gauge should be calibrated with the creation of a new calculation methodology.

3 MATERIALS AND METHODS

Investigations of the pump-ejector system was carried out on the laboratory bench (Figure 1) which worked in the following way. The power liquid (water) from the tank 1 enters the intake of a multistage centrifugal pump 2. Next, the power fluid is forced to the nozzle of the jet apparatus 3 and injects, depending on the experimental conditions, either gas from tank 1 or gas from the atmosphere, which is regulated by valves 12 and 13.

Figure 1. Diagram of the stand for the pump-ejector system investigation: 1 - liquid-gas tank; 2 - multi-stage centrifugal pump; 3 - ejector; 4 - differential pressure gauge; 5 - fluid meter; 6 - gas meter; 7, 8, 9 - manometers; 10 - pressure-vacuum meter; 11, 12, 13 - control valves and gate valves.

The flow rate of the power fluid injected into the nozzle is measured by a fluid meter 5. Depending on the conditions, the flow rate of the injected gas is measured by a differential pressure gauge 4 when high pressure gas is injected, or by a gas meter 6 when atmospheric air is injected. The pressures in front of the working nozzle of the jet apparatus and at the output from its diffuser were measured using manometers 7 and 8. The pressure at the ejector's intake was measured with a pressure – vacuum meter 10. Different operating modes and pressures were generated by a control valve 11.

Measured parameters during the experiment: fluid rate, gas rate from the tank, gas rate from the atmosphere, power pressure in front of the nozzle, pressure at the ejector's intake and output pressure. The efficiency of the ejector η_g during gas injection is determined by the ratio of the effective power N_e to total power N_t (Drozdov 2014):

$$\eta_g = \frac{N_e}{N_t} = \frac{Q_{g.in} P_{in} \ln \frac{P_o}{P_{in}}}{Q_p (P_o)} \quad (1)$$

$$= \frac{u_g P_{in} \ln \frac{P_o}{P_{in}}}{(P_p - P_o)},$$

where $Q_{g.in}$ – volumetric gas rate in the suction chamber;

P_{in} – pressure in the suction chamber (intake chamber);

P_o – outlet pressure of the ejector;

P_p – power pressure in front of the nozzle;

Q_p – volumetric power fluid rate;

$u_g = Q_{g.in}/Q_p$ is the volumetric injection coefficient in the suction chamber.

Technical water is used as a power liquid and air as a gas. Relative pressure drop:

$$\frac{\Delta P_c}{\Delta P_p} = \frac{P_c - P_{\pi p}}{P_p - P_{\pi p}} \quad (2)$$

where $\Delta P_c, \Delta P_p$ – pressure drops created by the jet apparatus and the working nozzle of the ejector respectively.

Differential pressure gauge DT-50 was used to determine the gas rate from the tank. Generally, it is used to measure the flow rate of non-aggressive gases, vapors and liquids by determining the pressure drop across the orifice plate or other throttle body.

Additional tubes were used for the accuracy and to increase the measurement range for gas rate (Figure 2). Were used 3 schemes of gas flow which dependences on the degree of gas rate.

The “right” scheme is used at pressures $P < 0.18$ MPa, which is activated by opening the valve 7 and closing the valve 6. The “left” scheme is used at pressures of $0.18 < P < 0.26$ MPa, where the valves open vice versa to the “right” scheme. The “general” scheme is used when $P > 0.26$ MPa, where both valves open. Theoretically, after getting the calibration curve at any pressure level, other pressure values can be obtained using the following equation:

$$Q_2 = Q_1 \sqrt{\frac{\lambda_1 P_1}{\lambda_2 P_2}} \left(\quad (3) \right.$$

where Q_1, Q_2 – the gas rates in the rheometer at pressures P_1 and P_2 respectively; λ_1, λ_2 – resistance values at P_1 and P_2 respectively.

For a quadratic zone of gas flow in a tube, as is well known $\lambda_1 = \lambda_2$, where at the same water level difference in the differential pressure gauge, we obtain:

Figure 2. Diagram of a differential pressure gauge with variable parameters of the measurement range: 1 - differential pressure gauge; 2 - manometer; 3 - copper tube (shortened); 4 - copper tube (elongated); 5, 6, 7, 8 - valves and gate valves.

$$Q_2 = Q_1 \sqrt{\frac{P_1}{P_2}}, \quad (4)$$

In article (Drozdov 1982) it is pointed out that in the calibration process where brass tubes with an internal diameter of 4-6 mm was used at pressure under 0.6 MPa, the resistance values are not equal $\lambda_1 \neq \lambda_2$. Analytical determination of λ with the required accuracy depending on pressure and flow rate by formula (3) is difficult to perform. Due to it, the calibration dependencies were built at the same pressures as in the experiments pressures values. Since our studies are carried out with 6 mm tubes at pressures below 0.6 MPa, it is necessary to introduce correction factors for formula (2).

Calibration of the differential pressure gauge was carried out in this way. Calibration curves were registered at pressures of 0.1; 0.14; 0.18; 0.22; 0.26; 0.3 MPa. Gas rates at appropriate pressures were calculated based on 0.1 MPa by the formula (4). After that, the deviations between the calculated and actual values were estimated. According to the deviations, correction factors were found, and flow rates based on new formula were calculated. Next will be presented the results.

4 RESULTS AND DISCUSSION

This section presents the results of experimental studies of the pump-ejector system and calibration of the differential pressure gauge.

4.1 Differential pressure gauge

Because of the calibration carried out, it was possible to achieve sufficient accuracy of the new calculation methodology (Table 1, Table 2, Table 3). The following formula was obtained for the “right” scheme:

Table 1. The results of the calibration of the differential pressure gauge for the “right” scheme.

P, MPa	Old method (Δ , %)	New method (Δ , %)
0,14	9,9	1,14
0,18	16,8	1,78
0,22	22,7	1,71
0,26	26,3	1,62
0,3	28,7	1,35

Table 2. The results of the calibration of the differential pressure gauge on the “left” scheme.

P, MPa	Old method (Δ , %)	New method (Δ , %)
0,14	9,1	1,37
0,18	15,4	1,11
0,22	18,9	0,99
0,26	23,1	1,01
0,3	25,4	1,15

Table 3. The results of the calibration of the differential pressure gauge on the “common” scheme.

P, MPa	Old method (Δ , %)	New method (Δ , %)
0,14	9,7	1,86
0,18	14,7	1,5
0,22	20,0	1,66
0,26	23,0	1,83
0,3	25,2	1,44

$$Q_2 = Q_1 * \sqrt{\frac{P_1}{P_2}} * \left(-5,04 * (\Delta P)^2 + 2,38 * (\Delta P) + 1,01 \right), \quad (5)$$

where Q_1, Q_2 – volumetric gas rates in differential pressure gauge at pressure P_1, P_2 respectively;

$$\Delta P = P_2 - P_1$$

During the calibration of the differential pressure gauge on the “right” scheme, the following results are obtained:

- according to the old method, the averaged inaccuracy is 20.88 %;
- according to the new method, the averaged inaccuracy does not exceed 1.8 %.

The next formula was obtained for “left” scheme:

$$Q_2 = Q_1 \times \sqrt{\frac{P_1}{P_2}} \times (-3,08 * (\Delta P)^2 + 1,75 * (\Delta P) + 1,03), \quad (6)$$

During the calibration of the differential pressure gauge on the “right” scheme, received the following indicators:

- according to the old method, the averaged inaccuracy is 18.52 %;
- according to the new method, the averaged inaccuracy does not exceed 1.9 %.

The next formula was obtained for “common” scheme:

$$Q_2 = Q_1 \times \sqrt{\frac{P_1}{P_2}} \times (-3,53 * (\Delta P)^2 + 1,83 * (\Delta P) + 1,03), \quad (7)$$

During the calibrating for the “common” system, we obtained the following indicators:

- according to the old method, the averaged inaccuracy is 18.52%
- according to the new method inaccuracy does not exceed 1.9%.

4.2 Characteristics of the pump-ejector system

After the calibration of the differential pressure gauge, the pressure-energy characteristics of the ejector were obtained (Figure 3, Figure 5). The maximum efficiency of ejector η_g during gas injection is obtained 0.325, where the relative pressure drop is $\Delta P_o / \Delta P_p = 0.315$, injection coefficient u_g in the suction chamber is 1.13 at intake pressure $P_{in} = 0.26$ MPa and outlet pressure $P_o = 0.636$ MPa. The minimum efficiency of ejector η_g during gas injection is obtained 0.245, where the relative pressure drop is $\Delta P_o / \Delta P_p = 0.294$, injection coefficient in the suction chamber is $u_g = 1.14$ under intake pressure $P_{in} = 0.05$ MPa and outlet pressure $P_o = 0.397$ MPa. It can also be noted that in the pressure range $P_{in} = 0.05 - 0.3$ MPa the injection coefficient in the suction chamber is varies from 1 to 1.14.

After that, a graph of maximum efficiencies η_g was plotted to the function of intake pressures P_{in} (Figure 4.). This graph shows that the difference between the maximum and

Figure 3. The ejector efficiencies η_g to the function of injection coefficient u_g .

Figure 4. The maximum efficiencies η_g to the function of intake pressure P_{in} .

Figure 5. The relative pressure drop $\Delta P_o/\Delta P_p$ to the function of injection coefficient u_g .

minimum values is 0.078. The value of η_g gradually increases to $P_{in} = 0.26$ MPa and after this point some decline is observed.

5 CONCLUSION

Research and calculations have shown that, the new calculation methodology of the differential pressure gauge makes it possible to calculate gas rates with an inaccuracy of no more than 1.8%.

The obtained pressure-energy characteristics for high pressures at the ejector's intake in the range from 0.05 to 0.3 MPa allow us to conclude that the maximum efficiency at this condition, do not exceed 32.5%. The volumetric injection coefficient rates range from 1 to 1.14. It is

worth noting that after the intake pressure of 0.26 MPa, there is some decrease in the efficiency, which can be assessed in further studies at higher intake pressure P_{in} .

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