Flue Gas-Simultaneous Water and Gas (Flue Gas-SWAG) Injection for Enhancing Oil Recovery

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Abstract. This paper discusses the possibility of utilization of exhaust (flue) gases by injecting them into the reservoir. Currently, injection of flue gases into the reservoir is not a widely used method for increasing oil production compared to CO₂ or N₂ injection. Most of technologies for injecting water-gas mixture using flue gas as a gas provide for water-alternating-gas injection. Only a few studies discuss simultaneous water-alternating-gas injection using flue gases. Moreover, there are few studies on creating a mixture of water and exhaust gases for co-injection by means of pump-ejecting systems into the reservoir. Therefore, in this work we propose a new improved diagram of the laboratory bench using exhaust (flue) gases to create a water and gas mixture for flue gas-simultaneous water and gas injection by means of pump-ejecting system.

1. Introduction

The current strategy of oil and gas companies is to reduce the share of flared associated petroleum gas (APG). Data on changes in the beneficial use of APG in Russian companies are shown in Figure 1.

![Figure 1. Beneficial use of APG in the Russian Federation.](image_url)

Increasing the beneficial use of APG is possible by injecting it into the reservoir in order to maintain reservoir pressure, increase oil recovery by injecting hydrocarbon gas or by implementing a water-
alternating-gas injection [1-4], as well as combustion of APG to generate own electricity in gas turbine and gas piston plants [5, 6], etc. Electricity in an oil field is used to run pumps and measuring and control equipment in the reservoir pressure maintenance system, electric centrifugal pump units during oil production from wells, refining and transporting oil and other areas. Figure 2 shows the percentage of energy consumption, case study of Gazprom Neft.

![Figure 2. Energy consumption at Gazprom Neft fields.](image)

Development of own generating capacities is economically attractive, as the cost of electricity produced at gas-fired power complexes (about 1.8 rubles per kWh) is lower than the average price of grid electricity in Western Siberia (2.5-2.7 rubles per kWh) [7]. In the Russian companies shown in Figure 3, the Percentage of generated electricity by own plants varies between 16-35% [7]. A by-product of this beneficial use of APG is exhaust gases.

![Figure 3. Percentage of self-generated by the company electricity from total consumption.](image)

A promising technology for injecting a water and gas mixture of has already been implemented in fields in various countries, with the largest number of pilot implementation of SWAG/WAG injection being in the USA, Russia, Canada and Norway [3,8].

2. Materials and methods
The main method for this paper is based on an analysis of global experience with the use of exhaust (flue) gases for oil production. A special focus has been placed on the studies of the gas used for oil displacement with pure gas or water and gas mixtures, and the conditions under which they are carried out.

An understanding of the types of studies involving exhaust gas in hydrocarbon production, as well as the technologies of injection has been formed on the basis of research.
A synthesis of the results of the exhaust gas efficiency analysis has to be made taking into account oil properties (high-viscosity, heavy, light, etc.) due to the difference in the displacement mechanism. Moreover, the mechanism of recovery is strongly influenced by reservoir conditions or thermobaric conditions in the laboratory model used, making it difficult to draw generalized conclusions.

In a number of laboratory studies [9, 10] of oil displacement by means of flue gases with different ratios of carbon dioxide and nitrogen (for example, 84.4 % N₂ and 15.6 % CO₂ or 75 % N₂ and 25 % CO₂) which are close in their composition to the flue gases from power plants or other possible industrial sources of such gases are most often used. Also, compositions similar to flue gases after in-situ combustion are synthesized [11] in order to assess the possibility of re-injection into the reservoir.

3. Discussion

The efficiency of water-alternating-gas injection technology has been documented in many papers [3, 12-16]. A number of studies [10-11, 17-19] have shown that this technology can be used with exhaust gas with higher efficiency compared to other technologies.

In order to select the optimal water-alternating-gas injection technology, it is necessary to consider not only the geological and physical properties of the field where the technology will be implemented, but also the field infrastructure, the availability of gas sources, the amount of gas and water, as well as the physical and chemical properties of fluids. The technique for the implementation of water-alternating-gas stimulation also remains an important challenge.

In works [20-22] the prospects of implementation of pump-ejecting systems for water-alternating-gas simulation has been discussed.

In work [20] research on realization of water-gas influence by means of pump-ejecting systems and using exhaust gases requires conducting experiments on a laboratory bench. The principal diagram of the test bench for studying the characteristics of liquid-gas ejectors (LGE), multistage centrifugal pumps and pump-ejecting systems on water and gas mixtures is given. In order to conduct research with exhaust gases, this bench is equipped with a gasoline internal combustion engine, a system for cooling gases from the engine, as well as control and measuring equipment for determining the parameters of gas flow.

As a result, this test bench allows using exhaust gases and liquid such as fresh water or electrolyte salt solution to create a mixture of water and gas. The schematic diagram of the improved test bench is shown in Figure 4.

The principle of operation of this bench is as follows. Water from the tank is pumped by the power pump through the cooling system of high-temperature exhaust gases emitted by the engine. The temperature of the flows is measured before and after the cooling system. Then water (working flow) enters the working nozzle of the ejector. The flow of exhaust gases is directed to the receiving chamber of the jet apparatus.

![Figure 4. Schematic diagram of the improved test bench.](image-url)
mixture is directed to the separator tank to separate the flow. After separation exhaust gases from the separator tank are drained into the ventilation system and water into the sewage system.

This bench implements an open circulation scheme for both gas and liquid, unlike the bench described in work [20].

For complete combustion of 1 m$^3$ of APG containing 76% of methane, 11% of ethane and 13% of propane, based on the equations of the material balance of the combustion processes of each component 8.2 m$^3$ of air mixture as an oxidizer is needed. The volume of combustion products is 9.2 m$^3$, including: nitrogen N$_2$ - 6.3 m$^3$, carbon dioxide CO$_2$ - 1.1 m$^3$, and water vapor H$_2$O - 1.8 m$^3$. Thus, the volume of exhaust gases is about 9 times more than the combusted volume of APG.

4. Conclusion
As a result of the study, it was found that the combustion reaction products from the utilization and beneficial use of associated petroleum gas for power generation can be used for injection into the reservoir by means of pump-ejecting systems. Thus, we proposed a new improved diagram of the laboratory bench to study the characteristics of pump-ejecting systems for simultaneous water-alternating-gas injection into reservoirs.

5. References
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