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MATHEMATICAL MODELING

FEATURES OF MATHEMATICAL MODELING OF IN-SITU COMBUSTION FOR PRODUCTION OF HIGH-VISCOSITY CRUDE OIL AND NATURAL BITUMENS

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Features of mathematical modeling of the process of recovery of high-viscosity crude oils and natural bitumens with use of in-situ combustion is examined based on a review of recent foreign publications. Hydrodynamic modeling is increasingly widely used. The importance of physical simulation on a "combustion-tube" apparatus, the results of which are irreplaceable in scaling-up the model to field dimensions, is demonstrated.

Key words: *in-situ, combustion, heavy oil, hydrodynamic modeling, THAI.*

The physico-chemical and production aspects of of catalysts in processes requiring in-situ combustion (ISC) and aquathermolysis [2, 3] for recovery of high-viscosity crude oils and natural bitumens have been examined in a previous paper [1]. This paper analyzes one of the principal problems that has been noted by specialists in this field – the complexity of mathematical modeling of the ISC process. Little light is shed on this problem in the Russian literature.

Hydrodynamic modeling permits on-going management of reserves, grouping them into previous stages of development in conformity with procedures optimal for their recovery, on-going economically based control of development, and planning for field-development systems that are optimal from the standpoint of profitability and reduction of recovery costs.

Here, ISC has already been successfully employed for 21 years in the southern section of Balol Field (India) wherein the oil-recovery factor (ORF has been increased from 13 to 50%, and the yield

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from 8 to 40 m^3/day, and flooding production reduced from 90 to 40% [4]. Among the disadvantages are blow-outs of injected air through one of the wells after the start of air injection (the well has been eliminated). The feasibility of further successful utilization of ISC was verified by testing in a pilot section, which had preceded theoretical substantiation. The following is a brief description of the subject: a 150×150-m grid of wells, a production pool located at depth of 1,049 m; its thickness is 6.5 m, the temperature in the pool is 70°C, the pressure is 10.5 MPa, the oil-saturation factor K_o = 0.,7, the void ratio K_v = 0.28, the penetrability is 8-15 D, and the viscosity of the oil is 0.3 Pa·sec. Dayal et al. [4] have indicated that physical modeling based on a "combustion-tube" apparatus makes it possible to acquire important data (the thermal conductivity of rock, crude, water, and gas, the heat capacity, etc.) that can be used for mathematical modeling (in the STARS CMG software package).

Mathematical modeling of the Suplako de Barco Field (Rumania), which is considered one of the largest ISC projects with a history of this method spanning more than 50 years was found to be not so successful; however, it has become a good source of scientific data [5]. A brief description of the subject follows: loose sands, depth of embedment of 35-220 m, thickness of up to 24 m, pressure of 1.65 MPa near the water-oil contact (WOC), initial pool temperature of 18°C, K_v = 0.32, penetrability of 5-7 D, and oil viscosity of 2 Pa·sec. Ruiz et al. [5] have successfully obtained good correlation with actual data only for recovery of water, while yields with respect to oil for low-yield wells correlate well with actual data; for high-yield wells, the correlation is poor. The overall behavior of the oil-yield curve has been successfully reproduced. The cause of lack of success may possible reside in failure to consider a second combustion front that develops later on.

Initial data for the modeling can be obtained from results of laboratory investigations on a "combustion-tube" apparatus, a device for investigation of oxidation kinetics (RTO), calorimetry at different heating rates (ARC), etc.

A mathematical model of the ISC process is under development at Cambridge University under the guidance of E. Mastorakos [6]. Selection of the following dimensionless parameters is proposed for ISC investigation: lag time prior to combustion, thickness of the combustion zone and the spread velocity of the front, and maximum extraction and extraction efficiency. The Damkohler number for crude oil (DaO) makes it possible to isolate three types of lag times prior to the start of combustion: limited by thermal diffusion, chemical singularities, and the amount of the oxygen supply. A Damkohler number also exists for coke (DaC), which defines the advance, or attenuation of the thermal wave. Judging from observations, the effectiveness of the ISC process will depend on the values of the DaC number, and to a lesser degree on the DaO number.

A new device [7] on which it is possible to study the combustion kinetics of crudes over a broad range heating rates (up to 30 deg./min) is being designed under the direction of A. Kovcheka from Stanford University; no similar tests have been previously conducted. At low heating rates (up to 3 deg/min), the results do not differ from data of earlier experiments. The new device will allow for limitation of heating rate to restrict the combustion rate of the crude. It is noted that the peaks of the low- (LTC) and high-temperature (HTC) combustion begin to merge into one with increasing heating rate. Only one peak exists when the heating rate is 30 deg/min.

A model [8], in which the iso-conversion principle is used for interpretation of apparent activation energy of the combustion process of crude has been developed to describe the ISC process. Variations in the temperature and composition of the gas were recorded during investigations. By reason of the exothermal character of the reactions, continuous monitoring of the heat being liberated is required for acquisition of reliable and consistent results. Three series of tests for various reactor designs, heating rates of the air, and volumes of crude have been conducted on the RTO unit; this has ultimately confirmed the reliability of the "model-free" iso-conversion principle, which is promising for simplification of interpretation of complex processes of *in-situ* combustion.

A combination of laboratory investigations, physical modeling, and rescaling procedures is called upon to ensure prediction of the probability of success, or lack thereof in performing ISC on the field scales [9]. Determination of combustion characteristics of crude on the laboratory scale is important for the investigation on the whole, while combination of the study of RTO kinetics and testing on a "combustion-tube" apparatus assumes acquisition of a reaction model with a high resolution, making it possible to predict the combustion process. This model is subsequently used to determine the amount of crude that can be transformed into fuel, and then the oxygen that is burned under a certain partial pressure, the velocity of the oxygen flow, type of rock, and its inhomogeneities, etc. Modeling on field scales is not based on Arrhenius' laws of kinetics, and as a result, it can be withdrawn from the constrictive nature of the finite-difference modeling of basic equations. Accordingly, the solution of these models consumes less time. Results obtained with use of the new scaling procedure differ little in their sensitivity to cell size.

Greaves et al. [10] have conducted accurate scientific verification of the model of the THAI process (Toe-To-Heel Air Injection). The kinetic model eliminates LTC reactions, since the THAI process is implemented for HTC temperature regimes. Ideal convergence is obtained between the predicted and actual crude yields, and good convergence of results based on the following dynamjc indicators: the profile of the residual coke, reduction of CO_2, and peak combustion temperature. This model can be up-scaled to field dimensions. Modeling has been conducted under conditions of dry combustion at high air-heating rates. The properties of the specimens investigated are: $K_o = 0.85$, degree of water saturation $K_w = 0.15$, initial temperature of 20°C, $K_v = 0.34$, penetrability of 2.3 D along the vertical, and penetrability of 11.5 D along the horizontal. The experiment was conducted in a three-dimensional 0.6×0.4×0.1-m compartment. Warming of the air was initiated after heating to 900°C.

' The THAI method was modeled in a section of the Athabasca field of high-viscosity oil (Canada) by a CMG STARS simulator [11]. A brief description of the subject follows: initial pressure of 2.6 MPa, temperature of 12°C, $K_o = 0.8$, $K_w = 0.2$, $K_v = 0.34$, horizontal penetrability of 6.7 D, and vertical penetrability of 5.36 D. Greaves et al. [11] note that the complexity of the processes that occur during ISC does not permit sufficiently correct up-scaling of results of the modeling on both one-dimensional "combustion-tube" units, and also three-dimensional units. A useful parameter that can be effectively simulated, however, is the spread velocity of the combustion front. As in the previous study, the LTC reactions also had not been defined more precisely during the modeling.

For the modeling in [11], five basic stages were isolated for recovery of the crude by the THAI method.

1. Initial warming. Injection of steam for initial heating and purification by movement of the injected air. Later on, heating of the air is initiated, and ISC is begun nearly instantaneously.

2. A sharp increase in the amount of injected air. An increase in oil yield to 68 m^3/day, and then a reduction to 46 m^3/day.

3. A period of maximum water recovery (172 m^3/day of water per 45 m^3/day of oil).

4. A basic crude-recovery period, yield of up to 60 m^3/day.

5. A period of stepwise reduction in recovery to zero.

Results of the modeling [11] indicated that the period of recovery was 10.8 years for the subject in question, after which blow-through of air into the recovering well occurred. At that moment, the ORF was 63%. It is expedient to discontinue the recovery for 10 years (at the end of the period of stable recovery). In this stage, the ORF had already attained a value of 60%. If it is considered that the period of profitability is 2.3 years in the case under consideration, use of the THAI method is economically justified.

Based on the fact that the method of cyclical and variable injection of steam yields essentially the same result, use of solar energy is proposed for thermal methods employed to improve oil yield [12]. This technology allows for a substantial reduction in CO_2 effluents, and accumulation of storage of the electrical power accumulated; for the high capital expenditures, this ensures a lessening of the dependence on prices established for gaseous fuel.

World experience indicates that for successful implementation of projects associated with development of fields of high-viscosity crudes and natural bitumens, it is necessary to conduct in mandatory order geologic-hydrodynamic modeling with use of specialized software packages (today, the most widely used packages are the SMG (STARS) and Schlumberger (Eclipse) programs). It is important to perform physical modeling on a “combustion-tube” unit, the results of which are irreplaceable when up-scaling the model to field dimensions. Despite the fact that in this stage of development of computer techniques, commercial simulators have a number of serious limitations, and computing power must also be shared for certain assumptions, use of the simulators will permit a considerable increase in the quality of the prediction.

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