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Research paper

Mathematical Model for Filling in the Dome-Separator Plant for the Elimination of the Near Bottom Hydrocarbon Flow

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Abstract

The work presents a mathematical model for the hydrocarbon crude extraction from the bottomhole zone by a cylindrical dome-separator. The proposed model allows determining the thermobaric conditions and dynamics of the boundaries of stratified phases in the installation during its operation and analyzing the complications associated with the possibility of formation of gas hydrates.

Keywords: *Gas Extraction, Hydrate, Dome-Separator, Hydrocarbons.*

1. Introduction

An important problem in oil recovery is the prevention of the consequences of uncontrolled discharge of hydrocarbon raw materials into the world ocean waters. The examples of such accidents include well breakouts in the Gulf of Mexico in 2010 and gas leakage at a producing platform in the North Sea in March 2012. The use of a dome-separator seems to be the most effective method of preventing such emissions [1, 2]. But this method leads to the formation of hydrates at the depths, corresponding to the conditions of their formation, which in the future may pose a problem for further pumping of hydrocarbons. Many publications have been devoted to hydrate formation mechanisms, for example [3-9].

Consider a dome-separator of a cylindrical shape, which will eliminate the formation of hydrate mass during the operation of the separator.

This work continues and further develop the works [10, 11], considering the hydrate strata depletion for various materials from which the dome-separator is made.

2. Basic equations

Figure 1 shows a schematic diagram of a cylindrical dome-separator, which is installed on the ocean floor, directly above the accident site. The segregation order shown is due to their densities $(\rho_g < \rho_o < \rho_h < \rho_w)$.

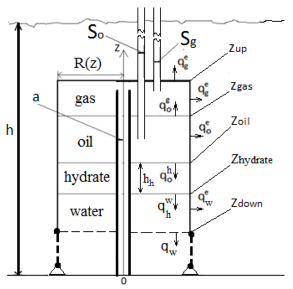

Fig. 1: Schematic diagram of the dome-separator

Where $R(z)$ – a dome radius; a – a well radius; z_{up}, z_{down} – the coordinate of the upper and lower boundaries of the dome; z_{gas}, z_{oil}, $z_{hydrate}$ – an interface between the phases "oil-gas", "oil-hydrate" and "hydrate-water"; h – the distance from the surface to the ocean floor; S_o, S_g – the sectional area of pipes for pumping oil and gas; h_h – the thickness of the hydrate layer.

The description of the change in the level of oil and gas during the filling of the dome-separator, assuming that there is no mass exchange between them, will be written as the equations of conservation of mass of hydrocarbons [12]:

$$\frac{dM_j}{dt} = m_j \qquad (1)$$

$$M_j = \int_{z_j}^{z_{j+1}} \rho_j \cdot F(z) dz, \qquad F(z) = \pi\left(R^2(z) - a^2\right)$$

$$\left(z_j < z < z_{j+1}\right),$$

where M_j – the mass of the phases; ρ_j – the density of phases; $F(z)$ – the sectional area of the dome in the coordinate z; m_j^+, m_j^- – input and extracted mass flow and gas consumption in the dome $(j = g, o)$.

The conservation of the mass of water in the dome will be described by the equation:

$$\frac{dM_w}{dt} = -\rho_w w_w F(z_h) \qquad (2)$$

where M_w – the mass of water; w_w – the rate of the water flow from the dome.

Conservation of mass of hydrate can be represented as follows:

$$\frac{dM_h}{dt}=F(z_h)j_h \quad (3)$$

where M_h – the mass of the hydrate; j_h – the intensity of the hydrate formation from an oil contact area unit.
To determine the average temperature of the phases in the dome, use the energy conservation law:

[illegible] (4)

[illegible] (5)

[illegible]

(6)

$$F(z)=\frac{dR(z)}{dz}$$

where q_g^e, q_o^g, q_o^e, q_o^g, q_o^h, q_w^e, q_h^w, q_w – heat fluxes shown in Figure 1; c_g, c_o – specific heat capacity of phases; T_g^+, T_o^+ – the temperature of input gas and oil; T_g, T_o, T_w – current average temperatures of the phases.
To determine the phase pressures in the upper part of the dome, use the hydrostatic balance condition:

[illegible] (7)

where p_{oc} – the pressure of the liquid column at the depth h; p_g – gas pressure under the dome; ρ_j – phases density; z_j, z_d – the coordinates of the boundaries of the phases and the lower base of the dome.

3. Description of heat and mass exchange

To close the reduced system, write the equation for the intensity of hydrate formation using the heat balance condition at the phase boundary:

$$j_h=\frac{-q_o^h+q_h^w}{l} \quad (8)$$

here q_o^h, q_h^w – heat flows from the oil to the hydrate layer and from the hydrate to the water.
The heat fluxes between the phases inside the dome-separator are described in the form [13]:

$$q_o^g=-\frac{(T_g-T_o)\lambda_g\lambda_o}{\lambda_g\sqrt{\pi\chi_g t}+\lambda_o\sqrt{\pi\chi_o t}},$$
$$q_o^h=\frac{(T_o-T_h)\lambda_o\lambda_h}{\lambda_o\sqrt{\pi\chi_o t}+\lambda_h\sqrt{\pi\chi_h t}},$$
$$q_h^w=-\frac{(T_h-T_w)\lambda_h\lambda_w}{\lambda_h\sqrt{\pi\chi_h t}+\lambda_w\sqrt{\pi\chi_w t}}, \quad (9)$$
$$q_w=-\frac{(T_w^- -T_w)\lambda_w}{2\sqrt{\pi\chi_w t}}$$

where q_o^g, q_o^h, q_h^w – the intensity of heat exchange per unit of contact area between oil and gas, oil and hydrate, hydrate and dome water layer, respectively, q_w – the heat exchange between the layer of water in the dome and under the dome per unit of contact area, λ_j – coefficient of thermal conductivity of phases $(j=g,o,h,w)$; χ_j – thermal diffusivity of phases; t – the time, counted from the start of filling in the dome with the hydrocarbon mixture.
According to the data given in [14], the biggest part of the associated gases is methane. Therefore, the temperature at the boundary z_h will be considered equal to the balance temperature of hydrate formation corresponding to the pressure p_{oc}, which, as noted in the works [15-18], for most hydrate-forming media (in particular, for methane and water), is well described by the empirical formula:

$$T_h(p_{oc})=T_{h0}+T_*\ln\left(\frac{p_{oc}}{p_{h0}}\right) \quad (10)$$

where T_{h0}, p_{h0}, T_* are empirical parameters.
Assume that the dome fills in for several days. Then, the motion of the phase boundaries is assumed to be at rest, which corresponds to the conditions for natural heat exchange through the dome wall. Therefore, to describe the thermal interaction of the phases with the surrounding ocean water through the wall of the dome-separator, adopt the following relations [19]:

$$q_j^-=\beta_c^-\left(T_j-T_c^-\right),\ q_c=\beta_c\left(T_c^- -T_c^+\right),\ q_c^+=\beta_c^+\left(T_c^+-T_w\right),$$
$$\beta_c^-=\frac{\lambda_j Nu_j}{2R(z)},\ \beta_c=\frac{\lambda_c}{\delta},\ \beta_c^+=\frac{\lambda_w Nu_w}{z_{j+1}-z_j} \quad (11)$$
$$Nu_j=B\left(Gr_j Pr_j\right)^n,\ Nu_w=B\left(Gr_w Pr_w\right)^n$$

where q_j^- – the intensity of heat exchange between the phases and the internal surface of the dome-separator wall per unit area of this wall $(j=g,o,w)$, q_c – the intensity of heat transfer through the wall of the dome per unit area of this wall area, q_c^+ – the heat exchange between the outer surface of the installation wall and the surrounding oceanic water per unit area of this wall, T_c^- – the temperature of the inner surface of the wall of the dome-separator, T_c^+ – the temperature of the outer surface of the wall of the dome installation, Nu, Gr, $\Pr$ – the Nusselt, Grashof and Prandtl numbers, B and n – the empirical constants for a vertical surface, λ_c – the wall material thermal conductivity (λ_p – polyurethane, λ_{st} – steel), δ – the thickness of the dome wall.

The heat flows q_j^-, q_c, q_c^+ must be equal, therefore from (11) obtain:

$$q_j^-=q_c=q_c^+=\beta\left(T_j-T_w\right) \quad (12)$$

where

$$\frac{1}{\beta}=\frac{1}{\beta_c^-}+\frac{1}{\beta_c}+\frac{1}{\beta_c^+} \quad .(13)$$

To simplify the task, assume that gas extraction to the ocean surface is not implemented.

4. Conclusions

The above-mentioned system of equations can be solved by numerical methods (particularly, by the Runge-Kutta method of the 4th order of accuracy) and allows describing such parameters as the movement of the phase boundaries, gas temperature and pressure inside the installation and changing the thickness of the gas hydrate layer formed during the start-and-installation work.

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