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Warm insulation of exhaust pipe when taking gas from the "dome - separator" installation from large depths

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Abstract. The article describes the impact of the use of polyurethane insulation on the tubes sclerosis by hydrate when gas is taken from the "dome-separator", installation that designed for emergency hydrocarbon collection at the bottom of the ocean. Such an installation collects hydrocarbons directly above the breakthrough point at the bottom of the ocean, and their transportation is carried out through pipes to the collecting vessel. Currently, in the conditions of the development of the Arctic shelf in order to increase the level of oil production, such breakthroughs can cause enormous damage to the ecosystem, in particular, in the Arctic Ocean, since living organisms that exists in the harsh conditions of these latitudes are more sensitive to changes in the environment. But during the passage of gas through the exhaust pipe in the presence of moisture and corresponding thermodynamic conditions, a hydrate formation process occurs. This phenomenon can cause the pipeline to overlap and impede the normal operation of the selection of hydrocarbons from great depths. To prevent these consequences, work suggests possible options for warming the pipeline. It is shown that sclerosis of a pipe extending to great depths can be prevented even with small values of polyurethane foam insulation.

1. Introduction

The "dome-separator" installation considered in this work can be used to prevent the consequences of oil and gas accidents at the bottom of the oceans [1, 2, 3]. Similar accidents related to well breakthroughs and hydrocarbon releases to the open ocean occurred in the Gulf of Mexico in 2010 and in the North Sea in 2012. The Dome-Separator collects hydrocarbons directly above the breakthrough site at the bottom of the ocean, and they are transported by pipes to the picking vessel.

This work is a continuation and further development of the work [2, 4].

2. Basic equations. Impulse and Energy equations

The formation of gas hydrates occurs when it corresponding thermodynamic conditions and there is water and light hydrocarbons [5, 6, 7].

We introduce the indices l and υ, which will correspond to the liquid phase and the vapor, w and g to water and the gas flow as a whole, and the index s to the parameters in the equilibrium state.

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Let us suppose that in the process of gas movement through the outlet pipeline, the temperature of the liquid and gas phases are equal over the entire cross section of the channel; phase transitions occurs in an equilibrium state and the gas flow is quasi-steady.

We considered mass gas flow m_g is constant:

$$m_g = m_{g0} = Const, \tag{1}$$

$$m_g = \rho_g \vartheta_g S , \quad S = \pi a^2 .$$

Here ρ_g and ϑ_g – the gas density and velocity; *S* и *a* – the area and radius of the “live section” of the pipeline. *a* and *S* are functions of the coordinate *z* and time *t*, because during gas extraction, hydrate will form on inner surface of shell of the discharge tube. The *z* coordinate will be counted from the input section into the pipeline. The pipeline is strictly vertical. To describe the thickness of hydrate near the shell there is $\delta_h = \delta_h(z,t)$. The radius of the pipeline is a_0. δ_{pp} is thickness of the polyurethane foam insulation. There is insulation between the steel shell (δ_{st}) and a layer of polyurethane (δ_p) (Figure 1).

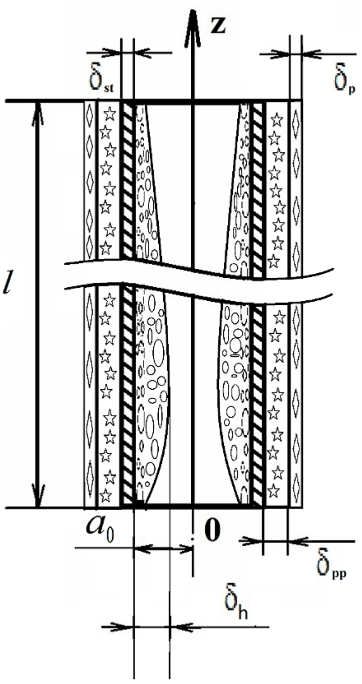

Figure 1. Scheme of pipeline

There is the water in gas in two forms: liquid (k_l) and gas (k_υ) phase. The mass concentration of water k_w is defined as:

$$k_w = k_l + (1 - k_l)k_\upsilon . \tag{2}$$

The gas flow in the stationary approximation is described by the impulse equation

$$m_g \frac{d\vartheta_g}{dz} = -S\frac{dp}{dz} - \rho_g g S - f . \tag{3}$$

Here p is the gas pressure.

The friction force generated during the selection of gas between its flow and the shell of the pipeline is written as [8, 9, 10]:

$$f = 2\pi a \tau , \qquad \tau = \lambda \frac{\rho_g \vartheta_g^2}{8} ,$$

where τ is hydraulic friction force, referred to the unit area of the inner surface of the pipeline and λ is coefficient of hydraulic resistance. If $\mathrm{Re} < 10^5$ the hydraulic resistance coefficient is determined by the Blasius equation [10]:

$$\lambda = \frac{0{,}3164}{\mathrm{Re}^{0,25}} .$$

There is heat generation because of steam condensation and the energy equation is written as:

$$m_g c_g \frac{dT_g}{dz} = \frac{m_g}{\rho_g} \frac{dp}{dz} + m_g l_w \frac{dk_l}{dz} - Q_{gen} , \tag{4}$$

$$Q_{gen} = 2\pi a q_{gen} ,$$

where l_w is specific heat of vaporization; T_g is gas temperature in the stream; q_{gen} is general heat transfer per unit area from the stream to the shell; c_g – specific heat of gas. The expressions for heat transfer from stream to the external environment:

$$\begin{aligned}
&q_g = \beta_g \left(T_g - T_h^{/} \right),\ q_h = \beta_h \left(T_h^{/} - T_h^{//} \right),\ q_{st} = \beta_{st} \left(T_{st}^{/} - T_{st}^{//} \right), \\
&q_{pp} = \beta_{pp} \left(T_{pp}^{/} - T_{pp}^{//} \right),\ q_p = \beta_p \left(T_p^{/} - T_p^{//} \right),\ q_w = \beta_w \left(T_{p1}^{/} - T_w \right) \\
&q_{gen} = q_g = q_h = q_{st} = q_{pp} = q_p = q_w , \qquad (5) \\
&q_{gen} = \beta_{gen} \left(T_g - T_w \right), \\
&\frac{1}{\beta_{gen}} = \frac{1}{\beta_g} + \frac{1}{\beta_h} + \frac{1}{\beta_{st}} + \frac{1}{\beta_{pp}} + \frac{1}{\beta_p} + \frac{1}{\beta_w} ,
\end{aligned}$$

$$\beta_g = \frac{\lambda_g \mathrm{Nu}_g}{2R} ,\ \beta_h = \frac{\lambda_h}{\delta_h} ,\ \beta_{st} = \frac{\lambda_{st}}{\delta_{st}} ,\ \beta_{pp} = \frac{\lambda_{pp}}{\delta_{pp}} ,\ \beta_p = \frac{\lambda_p}{\delta_p} ,\ \beta_w = \frac{\lambda_w \mathrm{Nu}_w}{l} .$$

where T_i^j are temperatures; index *i=g, h, st, pp, p, w* indicate respectively gas, hydrate, steel, polyurethane foam, polyurethane, surrounding water; index *j* with one hatch is for temperature on the inner surface of the layer and with two hatch is for temperature on the external surface of the layer; q_i are heat transfer rates per unit area; λ_i are thermal conductivity coefficients, *l* – length (height) of the pipeline.

Heat transfer from the gas stream to the pipe shell occurs in three modes [11, 12]. The first mode is implemented in the area where there is no hydrate formation. Then $q_h = 0$ и $\frac{1}{\beta_h} = 0$.

The second mode is characterized by heat sink:

$$q_g = \beta_g \left(T_g - T_s(p) \right), \tag{6}$$

where $T_s(p)$ is equilibrium hydrate formation temperature.

The third mode is describes by the diffusion:

$$q_g = \beta_g \left(T_g - T_h^{/} \right),$$

$$q_g + l_h j_h = q_w , \quad (7)$$

$$T_h^{/} = \frac{\beta_g T_g + \beta_w T_w + l_h j_h}{\beta_w + \beta_g} ,$$

where j_h is mass hydrate formation rate per unit area; l_h is specific heat of hydrate formation.

To describe the heat transfer, we determine the Nusselt number for gas ($\mathrm{Nu_g}$) and water ($\mathrm{Nu_w}$) flows [8, 10, 12, 13]:

$$\mathrm{Nu}_g = 0.021 \mathrm{Re}^{0.8} \mathrm{Pr}^{0.43}, \ \mathrm{Nu}_w = C \, \mathrm{Pr}^n \, \mathrm{Re}_w^m \quad (8)$$

where $\mathrm{Re}_w = \dfrac{w_w D_{equl}}{\nu_w}$; Pr is Prandtl number; w_w – flow rate for water; D_{equl} is equivalent diameter; ν_w is kinematic viscosity of sea water; n=0.35 is empirical coefficient; C and m *are* flow velocity and cylinder shape coefficients. To simplify, we assume that the velocity of the sea water flow current along the entire length of the outlet pipe is constant and varies from 0.25 m/s to 1 m/s. And that is why the coefficients will be C= 0.0026, m=0.8 [13].

The written equations (1), (3), (4), taking into account the Mendeleev - Clapeyron equation, the heat removal intensity Q_{gen} and hydraulic friction f, will form the equations system:

The obtained equations can be used for numerical calculations to describe changes in the temperature, pressure and the growth of hydrate deposits on the inner shell side of the pipe over time.

3. Results

Let us consider a deep-water well with parameters for the outlet pipe: a=5 cm; l=1500 m. We accept the following thermo-physical parameters: T_w=277 K; m_g=1 kg/s; R_g=520 J/(kg·K); μ_g=1028·10^{-8} kg/(m·s); c_g=2365 J/(kg·K); λ_g=0.03 W/(m·K); λ_p=0.25 W/(m·K); λ_{pp}=0.024 W/(m·K); λ_{st}=86 W/(m·K); l_w=1.7·10^6 J/kg; R_υ=461 J/(kg·K); p_{w*}=9.34·10^9; T_{w*}=4228; l_h=5·10^5 J/kg; k_υ=3·10^{-3}; ρ_h=910 kg/m^3; T_{h0}=283 K; p_{h0}=6.95 MPa; T_*=10 K. The calculation was carried out at the following thicknesses: δ_{st}=1 cm; δ_p=0.5 cm; δ_{pp}=0.5; 1 cm. The initial temperature and gas pressure at the inlet have been taken T_g^0=310 K; P_g^0=15 MPa.

Figures 2 and 3 shows the calculation results for an uninsulated and insulated pipeline, corresponding to the circuit shown in Figure 1 at various thicknesses of polyurethane foam. For three cases, three lines of different colors are shown: black for a steel pipe without insulation, red – δ_{pp}=0.5 cm and green – δ_{pp}=1 cm. The gas evacuation time from under the dome-separator is 35 hours, the flow rate of sea water w_w=0.25 m/s.

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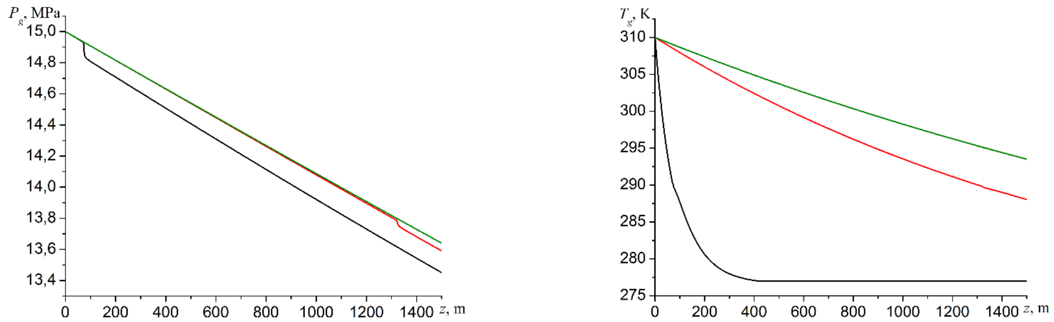

a b

Figure 2. Change of pressure (a) and temperature (b) of the gas along the outlet pipe at different thicknesses of insulation: δ_{pp} =0.5 cm – red line; δ_{pp} =1 cm – green line; without insulation – black line

It can be seen from the results that in the case of using a heater for a steel pipe in the form of a layer of polyurethane foam, the gas cools more slowly, unlike an insulated pipe, where its temperature drops quickly enough to ambient temperature.

The gas pressure along the pipeline pumping gas to the surface from under the dome-separator experiences a sharp drop in some areas, which can be explained by the adiabatic expansion when gas is passing through the narrowing region in the channel formed due to gas hydrate deposits on the walls. When using a heater with a thickness of 1 cm, such a sharp decrease is not observed, in contrast to the case of an insulated pipe, where it falls almost at its turn.

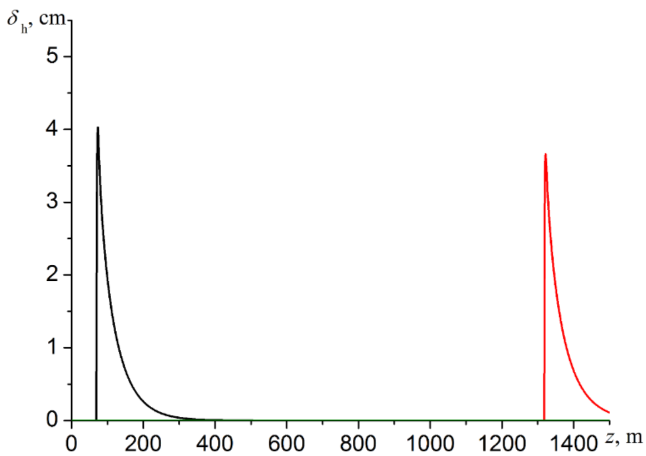

Figure 3. Change in the thickness of gas hydrate along the discharge pipe at different thicknesses of insulation: δ_{pp} =0.5 cm – red line; δ_{pp} =1 cm – green line; without insulation – black line.

Figure 3 shows the calculation results for the thickness of the gas hydrate layer formed on the channel walls. It can be seen that when the gas is pumped out after 35 hours, the pipe with a radius of 5 cm is almost blocked by gas hydrate formations. In this case, in the absence of insulation, a blockage forms in the pipe almost at the very bottom of the ocean, in the case of insulation, it is displaced to the surface and when the thickness of the polyurethane foam is 1 cm, sclerosis can be completely prevented along the entire length of the pipeline.

4. Conclusions

We consider the process of gas movement through an exhaust heat-insulated steel pipe, which contains moisture in the form of steam from large depths of the ocean from the dome-separator. This process is occurs into conditions for the formation of hydrates on the inner shell of the pipeline.

The calculation results for the gas pressure, temperature and growth of the hydrate layer on the channel shell are shown. It was found that during thermal insulation of a steel pipe with polyurethane foam insulation, even with small values of its thickness of 1 cm, channel obstruction by hydrates formed during gas evacuation from great depths can be prevented.

It can be concluded that when pumping gas from great depths from the dome-separator, thermal insulation of a steel pipeline with polyurethane foam insulation is an effective way to prevent the formation of gas hydrates and blockage of the pipeline.

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