International Journal for Innovative
Engineering and Management Research
A Peer Revieved Open Access International Journal
www.ijiemr.org

DOI: 10.48047/IJIEMR/V10/I04/09

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Volume 10, Issue 04, Pages: 31-35.

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MATHEMATICAL MODELING OF DYNAMICS FORMATION OF HYDRATES AT PIPELINE NATURAL GAS TRANSPORT

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Abstract: Hydrate formation is characterized by three conditions, namely: the presence of a hydrate former in the form of natural gas; the presence of a sufficient amount of water in natural gas; low pipe wall temperature, in the range below the dew point of moisture contained in the gas; high pressure.

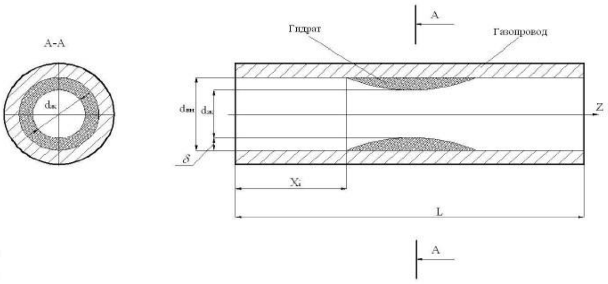
Keywords: gas hydrates, gas pipeline, pressure, temperature.

Introduction

Along with the main problems in transporting gas through gas pipelines differing in their functional type, there is the formation of gas hydrates in the pipeline cavity. This process is characterized by blockage of the flow section of the pipe, thereby reducing its throughput and leading to an emergency shutdown of the gas pipeline operation. The fight against gas hydrates, as well as their timely detection, make up a significant share of the budget of oil and gas companies. Thus, the reduction in operating costs for this category is of great interest from many companies in the oil and gas sector [1].

Figure 1 shows a diagram of a gas pipeline section with an indication of the area of hydrate formation and their geometric parameters.

Figure 1 - Scheme of the gas pipeline with the designation of the area of the hydration layer



D_{bh} - internal diameter of the gas pipeline (mm); d_{zh} - the diameter of the free area (mm); z - directions of the gas pipeline axis; xi - point of the beginning of hydrate formation (m); L - the length of the section under consideration (m) [2].

Hydrate formation is characterized by three conditions, namely: the presence of a hydrate former in the form of natural gas; the presence of a sufficient amount of water in natural gas; low pipe wall temperature, in the range below the dew point of moisture contained in the gas; high pressure [3]. However, it should be noted that the formation of gas hydrates may be accompanied by the absence of a liquid phase. In such cases, it is necessary to separate the dew point temperature of the dried gas by hydrates TTPг and the temperature of the gas dew point by liquid water TTPв [4].

Over time, in the course of gaining experience and conducting research in the field of pipeline transport, a number of measures have been developed to prevent and control the formation of gas hydrates.

– ways to prevent hydrate formation early:

– maintaining the gas temperature in the ranges excluding the temperature values below the dew point, using the method of periodic heating and applying a thickened layer of insulation to the gas pipeline;

– lowering the gas dew point temperature by lowering the pressure in the pipeline, as well as introducing inhibitors (methanol, ethylene glycol) that absorb water vapor in the gas;

– removal of water from gas using industrial gas drying.

– Methods used to combat hydrate formation:

– dissolution of hydrate plugs by pumping inhibitors into the pipeline. di- and triethylene glycol, calcium chloride, and methanol act as inhibitors;

– local heating of the pipe section subject to

– hydrate formation;

– pressure reduction in order to gradually decompose the hydrate plug. When using this method, measures are provided to prevent the occurrence of water hammer during the abrupt opening of valves to release gas after decomposition of hydrates [5].

The described methods make it possible to partially eliminate hydration deposits or prevent their appearance. When creating a mathematical model that reflects the formation of hydrates in the pipe, it is possible to determine the rate of hydrate formation and to determine the location of possible hydrate deposition.

To construct this model, a simplification is introduced and it is assumed that the working medium consists of two phases: gas (methane) and water. Gas movement is seen in a pipe; it is assumed that the moisture in the gas is sufficient to form hydrates along the entire length of the pipe. The value of the pipeline diameter has the following expression (1):

$$D = d_{BH} - \frac{\xi(z,t)}{2}. \qquad (1)$$

where d_{bh} is the inner diameter of the pipe, m; ξ (z, t) - time function of the thickness of the hydrate layer in the pipe, m.

The factors of temperature and pressure of hydrate formation are determined from the following system of equations (2),(3) [6]:

$$\begin{cases} \dfrac{dp}{dz} = -\left(\rho g + \dfrac{\psi\sqrt{\pi}M^2}{4\sqrt{S^5}\rho}\right). & (2) \\ \dfrac{dT}{dz} = \varepsilon\dfrac{dp}{dz} + \dfrac{\alpha w(Tw - T)\pi D}{M \cdot cp} - \dfrac{g}{cp}. & (3) \end{cases}$$

where z is the coordinate along the vertical axis of the pipeline, m; ρ is the density of natural gas, kg / m^3; g — acceleration due to gravity, m^2 / s; cp — isobaric heat capacity of the gas, J / K; αw is the coefficient of heat transfer from the gas to the hydration layer, W / m^2 • K;

S is the cross-sectional area of the pipeline, m^2;

ε is the Joule-Thompson coefficient;

ψ - coefficient of hydraulic resistance;

Tw is the pipe wall temperature, K;

M - gas mass flow rate, kg / s. M = const. Defined by the equation (4):

$$M = \rho VS. \qquad (4)$$

where V is the gas flow rate, m / s.

The initial conditions of the system (p, T) are taken based on the operating mode of the gas pipeline and are determined as follows:

$$\begin{cases} p(0) = p_H \\ T(0) = T_H \end{cases}$$

where pn and Tn are the pressure and temperature at the inlet to the gas pipeline respectively.

When the pressure of the system changes, the gas density changes; therefore, the density is determined by the equation of state for the gas:

$$\rho = \frac{p}{z0 \cdot R \cdot T}. \qquad (5)$$

R – gas constant, J / kg • K;

z0 – gas supercompressibility coefficient given by the Latonov-Gurevich equation (6):

$$z0(p,T) = \left[0{,}17\ln\left(\frac{T}{Tc}\right) + 0{,}73\right]^{\frac{p}{pc}} + 0{,}1\frac{p}{pc}. \qquad (6)$$

where pc, Tc are the pressure and temperature of supercompressibility, respectively.

For areas covered with hydrate, it is assumed that the wall temperature is equal to the gas-hydrate phase transition temperature, that is, Tw = Tf. The phase transition temperature is given by the following equation (7):

$$\mathrm{Tf(p)} = \beta 1 \ln\left(\frac{\mathrm{p}}{10^5}\right) + \beta 2. \qquad (7)$$

where β1, β2 are empirical coefficients.

For pipe walls free of hydrates, the pipe wall temperature is determined by the ordinary heat and mass transfer equation (8):

$$\mathrm{Tw} = \mathrm{Tp(D, z, t)}.$$

At the interface, the behavior of the system is determined by the Stefan condition (9):

$$\rho h \cdot lh \frac{d\xi}{dt} = -\lambda h \left.\frac{dTh}{dr}\right|_{r=d_{\text{вн}}/2-\xi} + \alpha w[Th(d_{\text{вн}}/2-\xi) - T]. \qquad (9)$$

where r is the radius vector starting at a point on the longitudinal axis of the pipe,

directed perpendicular to the longitudinal axis of the pipe.

ρh, lh, λh, Th are the density of the hydrate, the specific latent heat of formation of the hydrate, the thermal conductivity of the hydrate, and the temperature of the hydrate, respectively.

In the absence of a hydration layer on the outer and inner walls of the pipe, boundary conditions of the third kind are set (10):

$$\begin{cases} Th(r0-\xi) = Tf, \xi > 0 \\ \lambda p \left.\frac{dTp}{dr}\right|_{r=d_{\text{вн}}/2} = \alpha w(Tp - T) \\ -\lambda p \left.\frac{dTp}{dr}\right|_{r=D/2} = \alpha ps(Tp - Ts) \end{cases} . \qquad (10)$$

where Tp is the temperature of the pipe wall material, K;

Ts — ambient temperature of the annulus, K; αps is the coefficient of heat exchange between the wall and the environment;

αw is the heat transfer coefficient between the pipe wall and transported gas; λp - thermal conductivity of the pipe material, W / m • K.

According to equations (8) and (10), the equation for the pipe wall temperature has the form (11):

$$Tw = \frac{\lambda p(Ts - T)}{\alpha w \cdot d_{\text{вн}}/2\left[\frac{\lambda p}{\alpha w \cdot d_{\text{вн}}/2} + \frac{\lambda p}{\alpha ps \cdot D/2} + \ln\frac{D}{d_{\text{вн}}}\right]} + T. \qquad (11)$$

Taking into account the walls covered with a hydration layer, according to Stefan's equation (9) and equation (11) for a wall not exposed to hydrates, the basic equation for the formation of a hydration front is derived. (12) [7]:

$$\frac{d\xi}{dt} = \frac{(Tf - Ts)}{\rho h \cdot lh\left(\frac{d_{\text{вн}}}{2} - \xi\right)\left(\frac{\lambda p}{\frac{D}{2}\cdot \alpha ps} + \frac{\lambda p}{\lambda h}\ln\left(\frac{\frac{d_{\text{вн}}}{2}}{\frac{d_{\text{вн}}}{2} - \xi}\right) + \ln\left(\frac{D}{d_{\text{вн}}}\right)\right)} + \frac{\alpha w}{\rho h \cdot lh}[Tf - T]. \qquad (12)$$

To identify possible areas of hydrate formation, a pipe model was built in COMSOL Multiphysics. The model includes two main pipe sections of the same diameter and a branch pipe connecting them, which has a smaller diameter and acts as a throttling device.

The completed system configuration is shown in Figure 2.

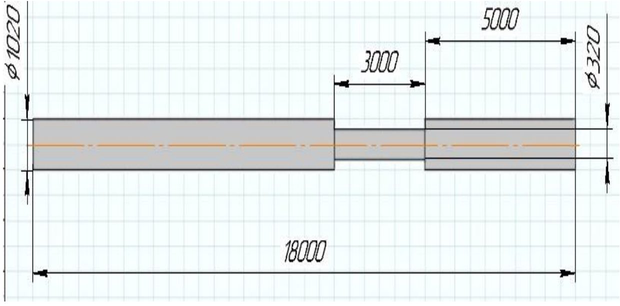


Figure 2 - Geometry of the experimental system with indication of dimensions.

–Since the program has a limited set of working environments, propane is chosen as the working environment for modeling. The numerical parameters of the model are presented below:

─- Speed at the entrance to the system 0.03 m / s;

─- Excessive pressure at the inlet to the system - 1 atm (101325 Pa);

─- Excessive pressure at the outlet from the system - 0;

─- Gas temperature at the inlet - 293 K;

─- Pipe wall temperature (environment) - 263 K.

The program provides for a simplified differentiation of an object ("Extra Course Mesh") into simple objects (triangles) to calculate the process parameters at all points of the system. The partitioning model of the system is shown in Figure 3.

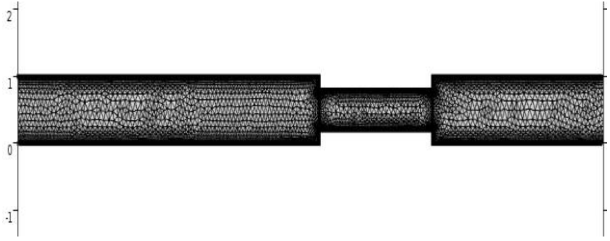


Figure 3 - Operation "Extra Course Mesh": splitting the model into simple sections

After obtaining the results of the calculation, the program derived a number of isosurfaces displaying the distribution of the gas flow rate, pressure and temperature. The velocity distribution during the passage of gas through the system is shown in Figure 4.

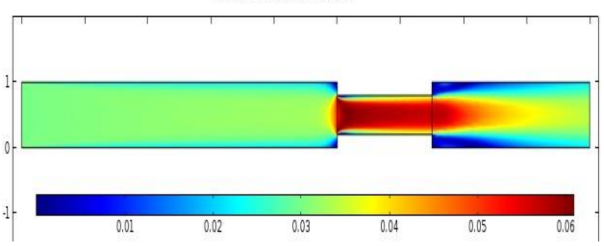


Figure 4 - Speed distribution in the system

From Figure 4, according to Bernoulli's law, the velocity in the converging flow is much higher than the flow velocity in the wider parts, which also causes the pressure drop in the narrow part of the pipeline. The pressure in the pipeline and its distribution is shown in Figure 5.

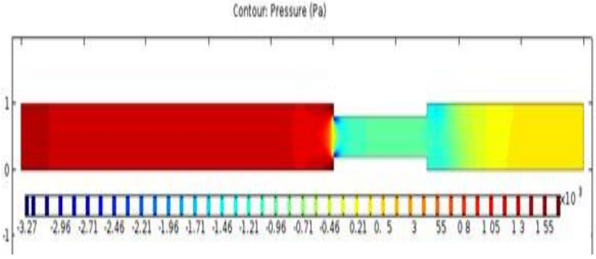


Figure 5 - Distribution of pressure over the section of the pipe model

The most significant pressure value is observed up to the throttling section. The pressure value degrades significantly when passing through a narrow section according to Bernoulli's law. However, the pressure builds up significantly after expansion in the system, as evidenced by a change in the color of the distribution. This fact may indicate a higher tendency towards the formation of gas hydrate in this area.

The temperature distribution of greatest interest for these studies is shown in Figure 6.

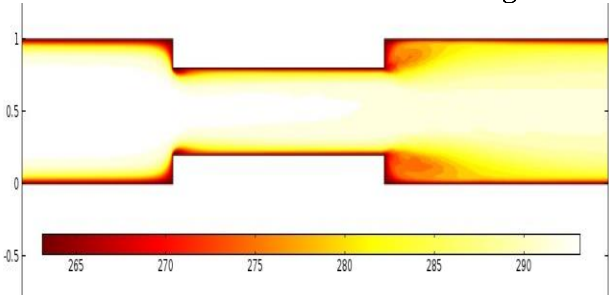


Figure 6 - Temperature distribution in the system

The coldest areas occupy the part located on the border of the narrow part of the pipe and the expanding part: according to the program's calculations, the temperature drops to 278 K. Taking into account the above-described fact about the pressure increase after expansion, it can be concluded that this area is in the zone of action of the risk of formation of gas hydrates ... The program built a graph shown in Figure 7, reflecting the temperature drop during the passage of gas through the system.

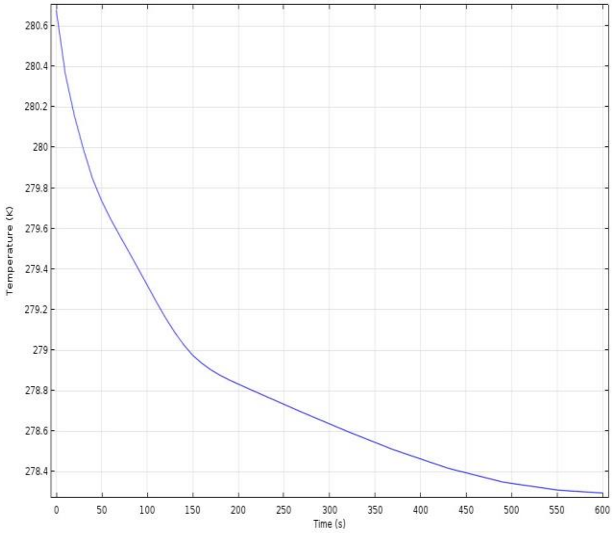


Figure 7 - Graph of temperature distribution in the boundary region of contraction-expansion

Thus, it is necessary to take measures to prevent (eliminate) icing in this area of the system. It is supposed to heat this area at a temperature of 320 K. The result of heating simulation is shown in Figure 8.

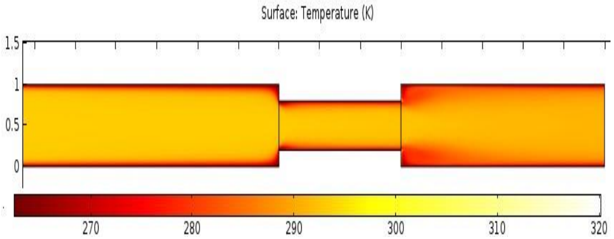


Figure 8 - Temperature distribution during heating of the area subject to hydrate formation

As a result of the improvements made, a temperature in this region of 299 K was obtained, which is a good indicator for preventing hydrate accumulation.

Thus, the constructed mathematical model makes it possible to timely diagnose possible foci of hydrate formation. According to equations (2) and (3), the distribution of temperature and pressure along the length of the pipeline is established and the numerical growth of the gas hydrate layer is determined with the determination of the temperature of the pipe wall, based on equations (11) and (12).

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