

# Influence of hydrate formation and wall shear stress on the corrosion rate of industrial pipeline materials

## Vliv tvorby hydrátů a mechanického pnutí na stěnách na korozní rychlost průmyslových trubkových materiálů

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*In the modern systems of transportation of oil, gas and condensate, in the units of regasification of liquefied natural gas, two-phase flows play an increasingly important role in technological equipment used in the chemical and oil refining industry, power engineering and other industries. All available studies on the formation of gas hydrates were mainly focused on their ability to clog pipes along their entire length. While their ability to cause (initiate) corrosion remains virtually unexplored. Therefore, to increase the efficiency of industrial pipelines it is necessary to study the joint effect of hydration formation and stresses of friction on corrosion of the pipeline. The mathematical model of pipeline corrosion has been further developed by considering the influence of the gas hydrate. The influence of pressure, temperature on the speed of corrosion processes is estimated and it is shown that under the most unfavorable conditions the corrosion rate under the action of gas hydrates can increase several times.*

*V moderních soustavách pro transport ropy, plynu a kondenzátu, v jednotkách na zplynování kapalného zemního plynu, dvoufázový tok hraje čím dál větší roli ohledně používaného vybavení ve chemickém a rafinérském průmyslu, energetice a dalších. Všechny dostupné studie o tvorbě hydrátů plynu byly zaměřeny hlavně jejich schopnost ucpávat potrubí po jejich celé délce. Zatímco schopnost způsobit korozní napadení zůstává víceméně nezmapovaná. Za účelem zvýšení efektivity průmyslových potrubí je nezbytné studovat současně vliv hydratace a napětí na korozi potrubí. Byl vytvořen matematický model pro korozi potrubí, který bere v úvahu vliv plynového hydrátu. Byl stanoven vliv tlaku, teploty na rychlost korozních procesů a ukazuje se, že za nejméně vhodných podmínek může vzrůst korozní rychlost až několikanásobně.*

## INTRODUCTION

In modern systems of transportation of oil, gas and condensate in the regasification of liquefied natural gas in the technological apparatus used in chemical and petrochemical industry, power engineering and other industries two-phase flows play an increasing role. With the introduction of pipelines transporting liquid-gas mixtures, before modern fluid dynamics was faced new challenges related to the study of the motion mechanism of two-phase flows. Knowledge of the basic laws of gas-liquid mixtures' motion in pipes and the ability to correctly calculate pressure loss and heat transfer are necessary for the construction and operation of two-phase systems. Therefore, the study of hydrodynamics and heat transfer of two-phase flows in pipelines and development of methods of their calculation is relevant to engineering practice the task [1]. Natural gas contains from 60 to 98% methane with impurities such as water

(H<sub>2</sub>O), carbon dioxide (CO<sub>2</sub>), hydrogen sulfide (H<sub>2</sub>S) and oxygen (O<sub>2</sub>). These impurities are capable of serious pipe corrosion and can initiate nucleation of gas hydrates. The formed hydrates can lead to partial or complete blockage of internal parts of the pipeline, and if it is not removed, it will lead to increased pressure inside the pipe and to a possible emergency. All existing studies of the gas hydrates formation have focused largely on their ability to clog pipes along the entire length while their ability to cause (initiate) corrosion remains practically unexplored [2]. Therefore, to increase the efficiency of industrial pipelines, it is necessary to study the joint effect of hydration formation and stresses on friction on corrosion of the pipeline.

With its nature of localized corrosion of metals is a stochastic [3] and is associated with two stochastic processes: the destruction of the passive film and repassivate open area [4]. Van Hank developed two-dimensional stochastic algorithm for the simulation of

the morphology of localized attack [5]. The algorithm is based on the assumption that the morphology of the corrosion effect depends on the balance of two processes: corrosion (leading to metal loss) and precipitation (leading to metal protection). This balance was presented in quantitative form using a single parameter: the ability to form deposits (sludge) ( $ST$ ):

$$ST = \frac{R_{FeCO_3}}{V_{cr}} \quad (1)$$

where  $R_{FeCO_3}$  is the rate of iron carbonate precipitate formation (mm/yr.),  $V_{cr}$  is the rate of corrosion (mm/yr.),

Nesik introduced changes to Van Hannick's model for the possibility of simulating a wider spectrum of localized corrosion morphology [6]. The two-dimensional  $ST$  algorithm as a single parameter was tied to a one-dimensional mechanistic model of  $CO_2$  corrosion in such a way that the localized influence morphology could be predicted as a function of the initial parameters such as temperature, pH, partial pressure of  $CO_2$ , velocity etc. The model, in which the uniform corrosion was considered, was expanded from the surface of the steel through the pores of the surface film and the adjoining layer of mass transfer to the turbulence of the solution. The concentration of each species was expressed by the mass balance equation [7]:

$$\frac{\partial(\varepsilon C_j)}{\partial t} = \frac{\partial}{\partial x} \left( \varepsilon^{1.5} D_j^{eff} \frac{\partial C_j}{\partial x} \right) + \varepsilon R_j \quad (2)$$

where

$$\frac{\partial(\varepsilon C_j)}{\partial t} \quad - \text{the accumulation};$$

$$\frac{\partial}{\partial x} \left( \varepsilon^{1.5} D_j^{eff} \frac{\partial C_j}{\partial x} \right) \quad - \text{resulting stream};$$

$\varepsilon R_j$  – the output or accumulation of products as a result of the chemical reaction;

$C_j$  – concentration of matter  $j$  (kmol/m<sup>3</sup>);

$\varepsilon$  – porosity of the film;

$D_j^{eff}$  – effective diffusion coefficient of a substance  $j$ ;

$R_j$  – entrance or accumulation of  $j$ -th grade as a result of all chemical reactions in which particular species are involved (kmol/m<sup>3</sup>·s<sup>-1</sup>);

$t$  – time (s);  $x$  – spatial coordinate (m).

Based on the results of this simulation, one could assume that inadequate protective films are the main cause of the origin and localization of corrosive lesions. The disadvantage of this model was the neglect of the electrokinetic component in the transport equation. The assumption that its effect on the total flow will be negligible due to the cumulative effect of different particles can be important. Also, the turbulent convection was replaced by turbulent diffusion, since the first one was difficult to detect in a turbulent flow. This, however, will affect the result of the model.

The development of corrosion-resistant models is another interesting aspect in the field of corrosion research. This is due to the fact that the quality of any analysis of fracture or operational reliability depends to a large extent on the model of corrosion. In different years, linear and bilinear models for corrosion damage, which were considered suitable for design, were later proposed and a stationary trilinear model with another power function was developed. Sors S. and Y. Garbatov proposed a nonlinear model describing the growth of corrosion damage in three phases: wear resistance of the coating, transition to visually evident corrosion with exponential growth, development and alignment of such corrosion [8]. Quin S. and Kui V. assumed that the rate of corrosion was determined by equating the volume of point corrosion to uniform corrosion [9]. The corrosion pattern of Pike D. also divided the nature of corrosion into three phases [10]. In the L. Ivanov's model, it was assumed that the transition phase of the nonlinear decrease in thickness increases with time in the form of a linear dependence (ratio) [11]. Wang V. collected a large thickness measurement database to establish a correlation between the regression of corrosion damage as a function of time that gives the value of the collected data. Garbatov subsequently used the Sors and Garbatov's model [8] for the Wang's data [12] and found that the non-linear model very well reflects the data [13]. Although all the models mentioned above consider insulation resistance, in the broadest sense, the time to initiate and develop the corrosion process, all of them are considered as a single parameter and different phases of corrosion are identified, but none of them took into account the influence of environmental factors.

To improve these models, Sors studied the effects of various environmental factors that were identified by Melchers on the characteristics of the corrosion of a steel plate, which is completely immersed in salty water [14, 15]. They proposed a new model of corrosion, based on a time-dependent nonlinear function. The model considered the effects of various environmental factors, including saltiness, temperature, dissolved oxygen, pH and flow velocity. This model is better than others, because instead of average corrosion damage data, it provides information on how corrosion has changed under the influence of external factors. However, this model was too cumbersome to calculate.

None of the presented models was focused on the development of a model taking into account the relationship between gas hydrate and corrosion. In fact, there are no literary sources where the possibility of hydrated breeds is considered to trigger the development of corrosion in natural gas pipelines.

The purpose of the work. Analysis of the influence of the structure of the gas-liquid mixture and hydrate formation on the speed of the pipeline corrosion.

## RESULTS AND DISCUSSION

According to the results of the corrode surfaces of the samples, held in the gas hydrate, the mechanism of its effect on the pipelines material corrosion was determined. The hydrate itself does not cause the corrosion, it only intensifies and localizes the effect of the reservoir water corrosive components (Fig. 1). At the first stage (the stage of the hydrate formation) the metal surface near it keeps covering with the passive films of the corrosion products, while this process stops on the metal surface under the hydrate. Besides, as the result of the hydrate crystals formation from the moisture absorbed by the corrosion products, the partial damage of the passive film occurs, as the volume of the formed crystals is in 2-3 time greater than that of water volume. After the hydrate dissociation (stage 2) the potentials difference is created between the described metal areas, which causes the appearance of the corrosion microgalvanic elements, which accelerate the metal solution in the less passive area. Further, when the thermobaric conditions favorable for the hydrate formation are created, it will be the most efficient in the area of the created corrosion action, as the latter is the crystallization center. With every next cycle of the gas hydrate "formation-decomposition" the depth of the corrosion defect increases. Thus, the mechanism of the mutual effect of the corrosion environment and the gas hydrates deals with the intensification and localization of the corrosion processes.

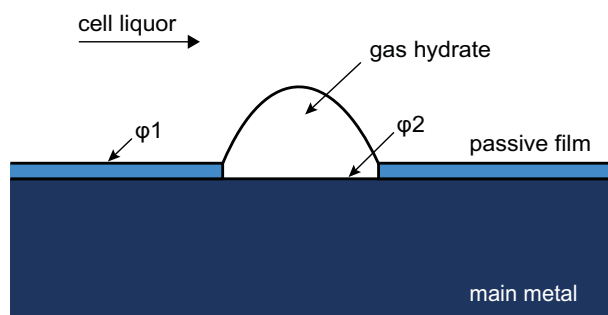


Fig. 1. The mutual effect of gas hydrate and reservoir water on the pipeline metal

Obr. 1. Vliv plynového hydrátu a zadržaná vodní kapka na povrchu potrubí

We propose the creation of a new and adaptation of the existing model [16] considering the friction stresses of the gas-liquid mixture, which is based on the principles of turbulent flow, closed system and conditions of the homogeneous phase and gas hydrate as a quenching agent. The model looked at carbon steel pipelines, which transported natural gas at various temperatures, pressures and pH levels.

For the averaged operating conditions, the following equation for the corrosion rate is proposed:

$$V_{cr} = K_{hydr} \cdot K_t \cdot f_t^{0.36} \cdot \left(\frac{\tau}{19}\right)^{0.146+0.0324 \cdot \log ft} \cdot f(\text{pH})_t \quad (3)$$

where  $K_{hydr}$  – coefficient of gas hydrate influence on the material corrosion rate,  $K_t$  – constant of the corrosion rate at different temperatures (Table 1);  $f(\text{pH})_t$  – pH factor;  $f_t$  – coefficient of fugacity;  $\tau$  – wall shear stress.

Tab. 1. Constant speed of corrosion at various temperatures [17] / *Korozní faktor pro různé teploty*

Temperatures (°C)	$K_t$
0	0,179
2,5	0,266
5	0,42
7,5	0,584
10	0,865
12,5	1,282
15	1,59
20	4,762

The model is based on the principles of turbulent flow, closed system and homogeneous phase conditions. When creating this model, attention is paid to the thermodynamic properties of the gas composition; this model is predictive in its essence, because it can be used to predict the residual life of the pipeline. We consider the model of the rate of internal corrosion that arose because of hydrate formation in the underwater segment of the natural gas pipeline. The developed model is based on NORSOK standard [17], Muhualdin and others [18] and the application of thermodynamic properties of the hydrate possible composition. The hydrate composition is as follows: 90% of the lattice of hydrate is water, 10 % – other components. Another component in this paper is the natural gas with the composition used in the laboratory for the eastern oil and gas region (Table 2).

Tab. 2. The composition of the gas used in the laboratory / *Složení použitého laboratorního plynu*

Component	Mole content (%)
Methane	80,9
Ethan	5
Propane	3
Butane	0,94
C <sub>5+</sub>	0,1
Carbon Dioxide	10,06

The pH factor within the operating temperature range is calculated by the equation (4) for the range of values  $3,5 \leq \text{pH} < 4,6$  or by equation (5) for  $4,6 \leq \text{pH} \leq 6,5$  [17]:

$$f(\text{pH})_t = 2,0676 - (0,2309 \cdot \text{pH}) \quad (4)$$

$$f(\text{pH})_t = 4,342 - 1,051 \cdot \text{pH} + 0,0708 \cdot \text{pH}^2 \quad (5)$$

The tension on the pipe wall caused by the gas-liquid mixture is a parameter that is taken into account when modeling the corrosion rate. A high wall shear stress in the tube can lead to the development of deep ulcer corrosion lesions, the so-called mesa-corrosion [19].

$$\tau = 0,125 \cdot \rho_m \cdot \lambda \cdot V_m^2 \quad (6)$$

where  $\rho_m$  – the density of the gas-liquid mixture ( $\text{kg}/\text{m}^3$ );  $\lambda$  – coefficient of hydraulic resistance;  $V_m$  – speed of the gas-liquid mixture ( $\text{m}/\text{s}$ ).

To calculate the coefficient of friction it is necessary to determine the flow structure of the gas-liquid mixture [20]. To do this, it is necessary to compare the dimensionless velocity of the mixture for the given conditions  $W_*$  and the limiting speed of the transition from the ring structure of the flow to the cork in the pipeline  $W_{\text{lim}}$ .

$$W_* = \frac{4 \cdot (Q_g + Q_w)}{\pi \cdot d^2} \cdot \left( \frac{\rho_w - \rho_g}{d \cdot \sigma} \right)^{1/4} \cdot \left( \frac{\rho_g}{\rho_w} \right)^{1/2} \quad (7)$$

where  $\rho_w$  is the density of water ( $\text{kg}/\text{m}^3$ );  $\rho_g$  is the density of gas under operating conditions ( $\text{kg}/\text{m}^3$ );  $\sigma$  is the surface tension coefficient ( $\text{H}/\text{m}$ );  $d$  – inner pipeline diameter ( $\text{m}$ );

$$W_{\text{lim}} = \left[ 2,2 - 0,0017 \cdot \left( \frac{\mu_g}{\mu_w} \right)^{-0,6} \right] \cdot 10^{(5,3 + 115 \cdot \frac{\mu_g}{\mu_w}) \cdot (1 - \phi)} \quad (8)$$

where  $\phi = \frac{Q_g}{Q_w + Q_g}$  – volumetric gas content; (9)

$Q_w$  – water flow ( $\text{m}^3/\text{s}$ );  $Q_g$  – gas flow, given to operational data ( $\text{m}^3/\text{s}$ )

When  $W_{\text{lim}} > W_*$  – the structure of the flow cork. Coefficient of hydraulic resistance for cork flow:

$$\lambda = \psi \cdot \lambda(\text{Re}, \varepsilon), \quad (10)$$

$$\lambda(\text{Re}, \varepsilon) = 0,067 \cdot \left( \frac{158}{\text{Re}_m} + \frac{2 \cdot \varepsilon}{d} \right)^{1/5} \quad (11)$$

where  $\varepsilon$  – roughness of pipes ( $\text{m}$ )

$$\psi = \left[ 1 - 0,78 \cdot \phi \cdot \left( 1 - e^{(-2,2 \cdot \sqrt{Fr_m})} \right) - 0,22 \cdot \left( 1 - e^{(-15 \cdot \frac{\rho_{g, st}}{\rho_{air}})} \right) \right] \cdot \frac{1}{1 - \phi} \quad (12)$$

Reynolds and Froude's Criterion for the mixture:

$$\text{Re}_m = \frac{4 \cdot (Q_g + Q_w)}{\pi \cdot d} \cdot \left[ \frac{\phi \cdot \rho_g}{\mu_g} + \frac{(1 - \phi) \cdot \rho_w}{\mu_w} \right] \quad (13)$$

$$\text{Fr}_m = \left[ \frac{4 \cdot (Q_g + Q_w)}{\pi \cdot d^2} \right]^2 \cdot \frac{1}{g \cdot d} \quad (14)$$

When  $W_{\text{lim}} > W_*$  – the structure of the circle current. The coefficient of hydraulic resistance for the ring current:

$$\lambda = \lambda_0 \cdot \psi \quad (15)$$

where, with  $\text{Re}_1 < 1500$ :

$$\lambda_0 = 64/\text{Re}_1 \quad (16)$$

$$\psi = 0,95 - (0,22 - 0,055 \cdot \text{Re}_1) \cdot \Phi \quad (17)$$

when  $\text{Re}_1 > 1500$ :  $\psi = 0,95$

$$\lambda_0 = 0,3164/\text{Re}_1^{1/4} \quad (18)$$

Reynolds' Criterion for liquid:

$$\text{Re}_1 = \frac{4 \cdot Q_w \cdot \rho_g}{\pi \cdot d \cdot \mu_g} \quad (19)$$

$$\Phi = \phi \cdot (1 - \phi)^3 \cdot g \cdot d \cdot \left( \frac{\pi \cdot d^2}{4 \cdot Q_w} \right)^2 \quad (20)$$

The actual water content is equal:

when  $W_* > 3,3$

$$1 - \phi = (0,523 + 0,02 \cdot W_*) \cdot (1 - \phi)^{(0,267 + 0,02 \cdot W_*)} \quad (21)$$

when  $W_* < 3,3$

$$1 - \phi = \{ 0,74 \cdot (3,3 - W_*) + [0,67 - 0,048 \cdot (W_* - 2)^2] \cdot (1 - \phi)^{(0,78 - 0,12 \cdot W_*)} \} \quad (22)$$

To bring the density of gas to the operational parameters, we use the dependence:

$$\rho_g = \rho_{g, st} \cdot \frac{P \cdot T_{g, st}}{Z \cdot P_o \cdot T} \quad (23)$$

where  $T_{st}$  – standard temperature ( $\text{K}$ );  $P_o$  – atmospheric pressure ( $\text{MPa}$ );  $Z$  – coefficient of compressibility of gas.

$$Z = 1 - \frac{0,0241 \cdot P_{pr}}{1 - 1,68 \cdot T_{pr} + 0,78 \cdot T_{pr}^2 + 0,01077 \cdot T_{pr}^3}, \quad (24)$$

where  $P_{pr} = \frac{P}{P_{pr}}$ ,  $\dot{O}_{pr} = \frac{\dot{O}}{\dot{O}_{pr}}$ ; (25)

$$P_{pc} = \sum_{i=1}^n P_{pc^i} \cdot y_i, \quad \dot{O}_{pc} = \sum_{i=1}^n T_{pc^i} \cdot y_i; \quad (26)$$

where  $P$ ,  $\dot{O}$  – given pressure and gas temperature;  $P_{pc^i}$ ,  $\dot{O}_{pc^i}$  – pseudo-critical pressure and gas temperature;  $P_{pc^i}$ ,  $T_{pc^i}$  – pseudo-reduce pressure and gas temperature;  $P_{pc^i}$ ,  $T_{pc^i}$  – critical pressure and critical temperature  $i$ -component. Gas density under standard conditions ( $\text{kg} / \text{m}^3$ ):

$$\rho_{g,st} = \sum_{i=1}^n \rho_i \cdot y_i \quad (27)$$

when  $n$  – number of components in the gas;  $y_i$  – molar (volumetric) concentration of components, fraction of unit.

$$\rho_i = \frac{M_i}{V} \quad (28)$$

when  $M_i$  – molecular weight of the  $i$ -component.

The density of the gas-liquid mixture:

$$\rho_m = \rho_g \cdot \phi + \rho_w \cdot (1 - \phi), \quad (29)$$

speed of the gas-liquid mixture:

$$V_m = \frac{Q_g + Q_w}{F} = \frac{4 \cdot (Q_g + Q_w)}{\pi \cdot d^2} \quad (30)$$

the gas flow is given to the operational parameters:

$$Q_g = Q_{g,st} \cdot \frac{Z \cdot T \cdot P_o}{T_{st} \cdot P} \quad (31)$$

dynamic viscosity coefficient of gas:

$$\mu_g = 5,1 \cdot 10^{-6} \cdot [1 + \rho_{air} \cdot (1,1 - 0,25 \cdot \rho_{air})] \cdot \quad (32)$$

$$\cdot [0,037 + T_{pr} \cdot (1 - 0,104 \cdot T_{pr})] \cdot \left(1 + \frac{P_{pr}^2}{30 \cdot P_{pr}^{-1}}\right)$$

The dynamic coefficient of water viscosity at the given pressure and temperature is determined by the formulas:

when  $273 \text{ K} \leq T \leq 293 \text{ K}$

$$\mu_w = 10^{\left(\frac{1301}{998,333 + 8,1855 \cdot (T - 293) + 0,00585 \cdot (T - 293)^2}\right) - 1,30233} \cdot 10^{-3} \quad (33)$$

when  $293 \text{ K} < T \leq 373 \text{ K}$

$$\mu_w = 1,002 \cdot \left[10^{\left(\frac{1,3272 \cdot (T - 293) - 0,001053 \cdot (T - 293)^2}{(T + 378)}\right)}\right] \cdot 10^{-3} \quad (34)$$

However, in this study the equation (33) was considered, since the temperature range which is used is within these limits. In addition to the water molecule, each other molecule in the hydrate is gaseous. However, under high pressure conditions, it is no longer possible to consider the ideal gas situation, since the partial gas pressure must be multiplied by its volatility constant. The general equation of hydration volatility, which consists of many components, can be expressed.

$$f_T = a \cdot \sum_{i=1}^n P_i \quad (35)$$

Required data for components  $\omega_i$ ,  $T_{pc^3}$ ,  $P_{pc^3}$ ,  $M_i$  hydrate is shown in Table 3.

The coefficient of volatility, as a function of temperature and pressure, is determined by the formulas [21]: at  $p < 25 \text{ MPa}$ :

$$a = 10^{P \cdot \left(0,0031 - \frac{1,4}{T}\right)} \quad (37)$$

at  $P > 25 \text{ MPa}$ :

$$a = 10^{2,5 \cdot \left(0,0031 - \frac{1,4}{T}\right)} \quad (38)$$

Tab. 3. Relevant values for hydrate components [21] / *Odpovídající data pro složky hydrátu*

Component	$\omega_i$ (%)	$T_{pc^3}$ (K)	$P_{pc^3}$ (MPa)	$M_i$ (kg/kMol)
CH <sub>4</sub>	8,09	190,60	4,599	16,043
C <sub>2</sub> H <sub>6</sub>	0,5	305,3	4,872	30,07
C <sub>3</sub> H <sub>8</sub>	0,3	369,8	4,248	44,097
<i>n</i> -C <sub>4</sub> H <sub>10</sub>	0,094	425,1	3,796	58,124
<i>n</i> -C <sub>5</sub> H <sub>12</sub>	0,01	469,7	3,370	72,151
CO <sub>2</sub>	0,1006	304,2	7,383	44,011
H <sub>2</sub> O	90	647,1	22,055	18,016

Tab. 4. Parameters used for test simulation / *Vstupní parametry pro simulaci*

Parameter	Value
Working temperature (°C)	0; 1; 2; 3; ... 17; 18; 19
Working pressure (MPa)	1; 1.5; 2; ... 9; 9.5; 10
Atmospheric pressure (MPa)	0,101325
Temperature under standard conditions (K)	293
Average fluid flow in the pipeline (ths.m <sup>3</sup> /day)	0,1
Average gas flow in the pipeline (ths m <sup>3</sup> /day)	10
range pH	3.5 – 6.5
Inner pipe diameter (m)	0,086

However, equation (37) is used for this study, since most operations in the pipeline are performed under pressure below 25 MPa. In addition, hydrates can be formed even at a pressure of 2.5 MPa. Output data for evaluating the characteristics of the model are shown in Table 4.

Influence of temperature on the speed of corrosion, according to the forecast model presented in Figure 2. It is observed in the figure that the rate of corrosion increases with temperature, it is fully consistent with the various experimental and predictive models. This may be due to the secondary effect of temperature on the solubility of the corrosion substance, which is the most common factor affecting corrosion. Studies have shown that the change in the working temperature has an impact on many other factors, which, in turn, affect the rate of corrosion. From Figure 2 in the range of the investigated temperature and pressure of hydration formation, the minimum corrosion rate for the pipeline is approximately 1.1 mm/year which characterizes with uniform damage



to the wall of the pipeline material. This value is due to the fact that the hydrate breaks will increase in size and this will lead to the development of point and slit corrosion.

With increased working pressure, the rate of erosion corrosion increases (Fig. 3). The obtained value of the pressure ratio and corrosion rate is reliable given the thermodynamic properties of hydrate formation. Increasing working pressure leads to an increase in the speed in the pipeline, which in turn increases the mixing in the transported fluid and this helps to hydrate through turbulence. On the narrowing due to the formed gas hydrate there is a temperature difference under the effect of the Joule-Thompson effect (expansion of the gas when it is cooled), as a result, there is an increase of existing ones. The presence of welds (branch pipes, tees, etc.), dirt, scales, cracks and grains also contribute to the formation of germs, and unbound water acts as a reinforcing agent, since the contact area of gas and water is a good point in the formation of the hydrates' nuclei. Over time, formed hydrates increase quantitatively and in size due to their accumulation inside the pipeline.

From Figure 4, it follows that the rate of corrosion increases with a decrease in the pH, which is explained by the fact that in more acidic environments, corrosion reactions occur faster. To study the influence of the operating mode on the corrosion rate of the industrial pipeline material, it is necessary to implement such a calculation algorithm (Fig. 5).

## CONCLUSIONS

Mathematical models of internal corrosion developed according to the Norwegian standard (NORSORK 2005) and Mohyalindin and others (2011) by introducing the influence coefficient of the gas hydrate. The proposed model enables prediction of corrosion processes on gas pipelines considering hydrate formation.

By developed mathematical model calculated influence of pressure, temperature on the speed of corrosion processes is estimated and it is shown that under the most unfavorable conditions the corrosion rate under the influence of gas hydrates can reach 1.1 mm/year. With this indicator, the pipeline suffers significant damage in the absence of immediate repair measures.

The sharp increase in the corrosion rate negatively affects the operation of the pipeline, reducing the operational life of the pipeline. Increasing working pressure raises the temperature of hydration, but at the same time leads to an increase in the erosion corrosion rate. Also, it is shown the influence of the pH environment in which the gas hydrate is formed, according to the results of the prediction model, the corrosion rate increases with the level of the environment acidification.

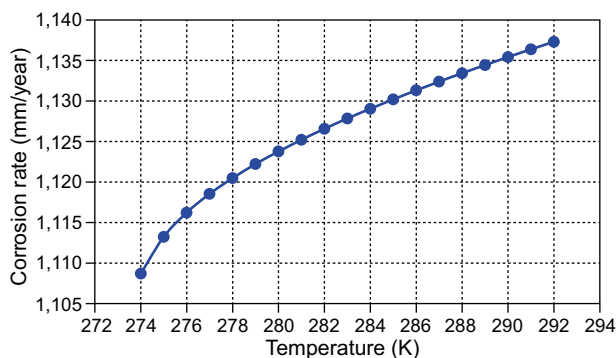


Fig. 2. The calculated rate of corrosion, depending on the temperature change at pH = 6.0 and pressure 3 MPa  
Obr. 2. Výpočet korozní rychlosti jako funkce teploty při pH 6 a tlaku 3 MPa

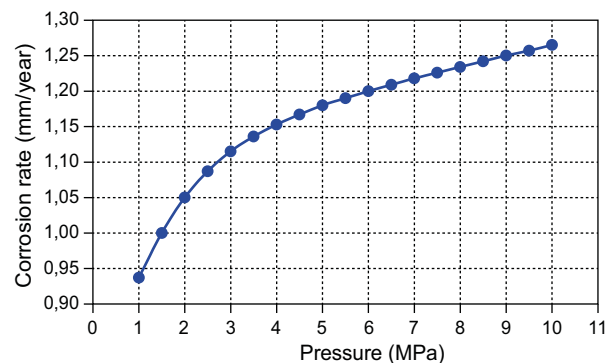


Fig. 3. The calculated rate of corrosion depending on the pressure change at pH = 6.0 and temperature 2,5 °C  
Obr. 3. Výpočet korozní rychlosti jako funkce tlaku při pH 6 a teplotě 2,5 °C

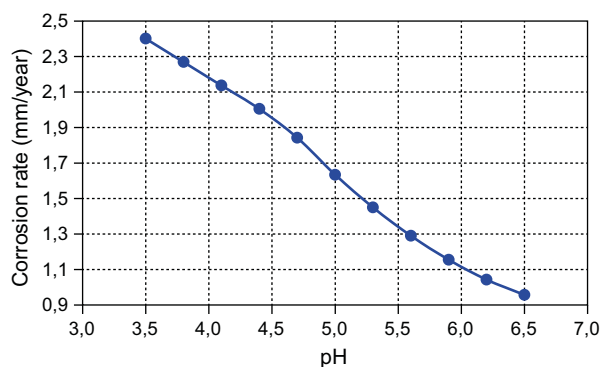


Fig. 4. Calculated corrosion rate depending on the pH indicator at a pressure of 3 MPa and a temperature of 2.5 °C  
Obr. 4. Výpočet korozní rychlosti jako funkce pH při teplotě 2,5 °C a tlaku 3 MPa

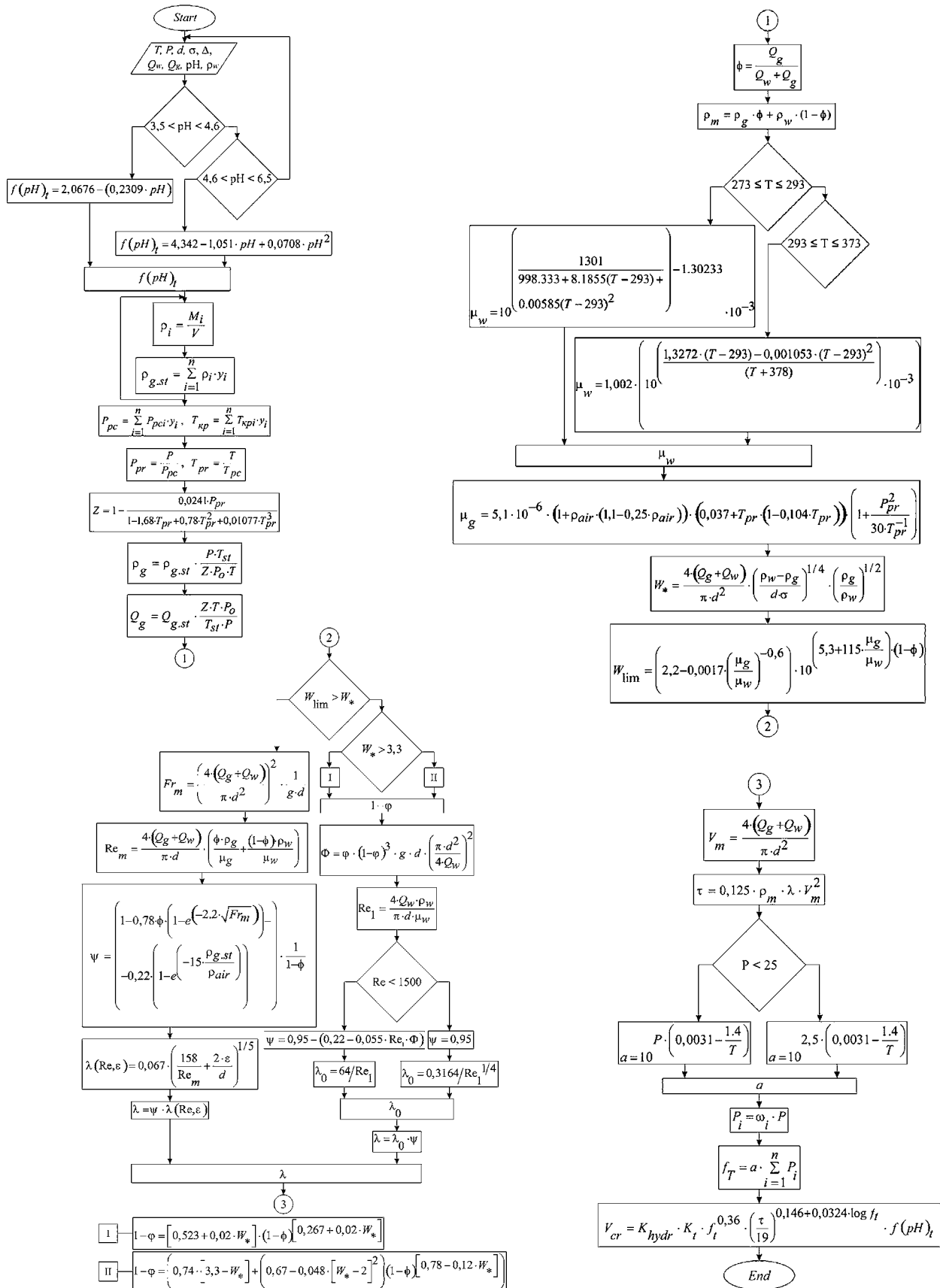


Fig. 5. Calculation algorithm for influence of the operating mode estimation  
 Obr. 5. Výpočetní algoritmus pro vliv operačního nastavení

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