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Methodological basics of gas-drainage pipeline engineering for transporting wet firedamp in winter time

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ABSTRACT: The work presents the developed mathematical model of heat-and-mass transfer processes of the atmospheric air with humid firedamp transported through surface pipelines in winter seasons. In terms of the integral of a differential equation of the convection-diffusion heat transfer in a pipeline, methodological fundamentals have been worked out to calculate the critical length of mine surface pipelines when their inside surface freezing process do not occur. Engineering methods of calculating thermodynamic properties of the methane-air mixture are provided.

1 INPRODUCTION

In view of energy independence support, the use of degassed coalmine methane has good prospects in Ukraine. This conditions the development of pipeline systems working all year round on the coal mine surface. The firedamp, or methane-air mixture (further MAM), at the output of vacuum-air pumps of mine-gas-drainage plants contains suspended moisture and has one hundred percent relative humidity. On cooling MAM, there occurs condensation of water vapour which MAM contains. With negative values of the free-air temperature, the condensation product transforms directly into ice which narrows the inner dimension till their complete clogging. As freeze protection, thermal insulation of gas-drainage pipelines is applied. However, the issue of using thermal insulation in order to avoid overspending must be solved with reference to a thermal design considering the MAM thermodynamic properties and the environment, remoteness of vacuum-pump stations from consumers, and other factors. Nevertheless, at the present time there are no methods which allow doing such calculations.

The purpose of the work is to develop methodological fundamentals to calculate the preassembled length of the pipelines transporting the degassed coalmine methane with negative values of the free-air temperature.

2 THE MAJOR PART

The pipeline design scheme of a line element is depicted in Figure 1 being x a longitudinal coordinate, m; r a transverse coordinate, m; T is the MAM temperature, K; T_0 is the free-air temperature, K; R is the pipeline radius, m; S is the cross-section area of the pipeline, m^2.

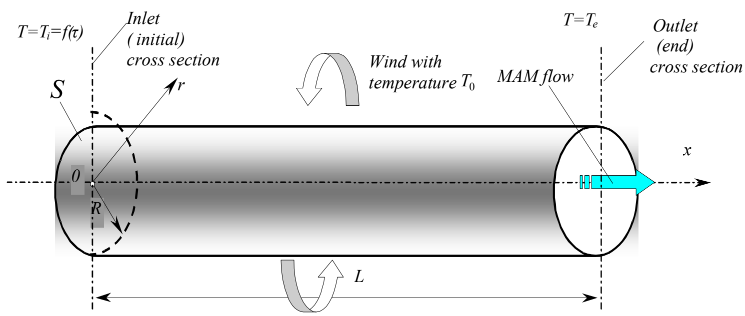

Figure 1. The pipeline design scheme.

Let's accept that up to the point of feeding MAM into the pipeline, the temperature inside the pipeline was equal to the temperature in the ambient atmosphere T_0, and the MAM initial temperature T_i increases from level T_0 to critical values T^* within specific time frames. The heat flux rate on the pipeline surface into the ambient atmosphere is defined with Fourier's law. Subsequently, in differential calculus the mathematical formulation of the heat-and-mass transfer problem with the MAM moving in the pipe takes the form of equation of convection-diffusion heat transfer in the pipe (Tsoy 1984)

$$\frac{\partial T}{\partial \tau} + u\frac{\partial T}{\partial x} = a\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right), \tag{1}$$

with the initial condition

$$T(x,r,0) = T_0, \tag{2}$$

and the boundary of third kind

$$T(0,r,\tau) = f(\tau), \tag{3}$$

$$-\lambda\left.\frac{\partial T}{\partial r}\right|_{r=R} = k\cdot\left(T|_{r=R} - T_0\right), \tag{4}$$

where τ – time, s; u – MAM velocity in the pipeline, mps; a – MAM temperature conductivity coefficient, m^{2}ps; λ – MAM thermal conductivity coefficient, W/m·K; k – heat transfer coefficient, W/m^2·K.

In expressions (1), (4) the values of the temperature conductivity coefficient and the heat transfer coefficient are estimated according to (Mikheev & Mikheeva 1973)

$$a = \frac{\lambda}{\rho\cdot c}, \tag{5}$$

$$k = \frac{1}{\frac{1}{\alpha_g} + \frac{\delta}{\lambda_T} + \frac{1}{\alpha_a}}, \tag{6}$$

where ρ – MAM density, kg/m^3; c – MAM heat capacity, J/(kg·K), α_g – coefficient of heat-exchange between the MAM and the inner surface of the gas pipeline , W/(m^2·K); δ – gas pipe wall thickness, m; λ_T – thermal conductivity coefficient of gas pipeline material, W/(m·K); α_a – coefficient of heat-exchange from the gas pipeline outer surface to the ambient air, W/(m^2·K).

The MAM thermophysical properties which are included in (1)–(6) depend on the dynamics of MAM temperature and pressure changes over a distance and time. Let's assume that the MAM pressure drop along the pipeline length as a result of friction force is inconsiderable compared to absolute pressure while the MAM enters the gas pipeline. In this case according to the law of gas mass conservation with steady-state motion, the MAM density can be considered constant (Baskakov 1982 & Loytsianskiy 1970). Consequently, while doing practical calculation we will take the values of the MAM thermophysical properties in the context of a steady mode of the MAM average temperature and constant pressure.

With regard to (5) we will write Equation (1) as follows

$$c\rho\frac{\partial T}{\partial \tau} + c\rho u\frac{\partial T}{\partial x} = \lambda\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right). \tag{7}$$

Equation (7) accounts for both longitudinal and radial heat transfer. The pipeline radius is considerably smaller than its length. Consequently, transverse heat flow is considerably smaller than the longitudinal one. That is why while modelling the MAM heat and mass transfer process in the gas pipeline, it is worth using the MAM averaged temperature in the cross section (Bobrovskiy 1972). To do this, we multiply both parts of Equation (7) by r, integrate over this coordinate within the limits of 0 to R and divide by the cross-section area of the pipeline S. As a result, Equation (7) takes on the following form

$$c\rho\frac{\partial \overline{T}}{\partial \tau} + c\rho u\frac{\partial \overline{T}}{\partial x} = k\frac{\Omega}{S}\left(T_0 - \overline{T}\right), \tag{8}$$

$$\overline{T} = \frac{1}{S}\int_0^R r\cdot T\cdot dr, \tag{9}$$

where Ω – pipeline perimeter, m.

After solving Equation (8) under the boundary condition (3) with the initial condition $T(x,0) = T_0$ we get the formula for the length estimation of the gas pipeline whose inner surface is ice free (Alabiev 2006)

$$L = \frac{1}{4}d\frac{1}{St}ln\frac{T_i - T_0}{T_e - T_0}, \tag{10}$$

where d – gas pipeline diameter, m; T_i, T_e – MAM temperature at the beginning and the end of the pipeline, ºC; T_0 – atmospheric air temperature, ºC; St – Stanton number.

As (10) shows, the estimation of the critical length of the gas pipeline resolves itself into estimation of the Stanton number St which is connected to the Nusselt number (Nu) and the Peclet number (Pe) with relation (Mikheev & Mikheeva 1973)

$$St = \frac{Nu}{Pe} . \tag{11}$$

Peclet number is defined as (Mikheev & Mikheeva 1973)

$$Pe = \frac{u \cdot d}{a} , \tag{12}$$

in which the MAM movement velocity in the pipeline is estimated with formula

$$u = \frac{Q}{S} , \text{[m/s]} \tag{13}$$

where Q – MAM consumption in the pipeline, m^3/s; S – stands for the pipeline cross section.

The MAM thermal conductivity coefficient in formula (5) to estimate the MAM temperature conductivity coefficient can be defined as average weighted for the thermal conductivity coefficients of the air and methane

$$\lambda = (1-\psi) \cdot \lambda_a + \psi \cdot \lambda_m , \text{ W/(m·°K)}, \tag{14}$$

where λ_a – air thermal conductivity coefficient; λ_m – methane thermal conductivity coefficient; ψ – methane concentration in the MAM, unit fraction.

The air thermal conductivity coefficient λ_a depends on the temperature and is accepted according to Table 1 or is estimated with a high degree of accuracy according to empirical formula

$$\lambda_a = \frac{2.44 + 0.0078 \cdot T}{100} , \text{[W/(m·°K)]} \tag{15}$$

Table 1. The air thermal conductivity coefficient.

Temperature, °K	243	263	283	303	323	333
$\lambda_a \cdot 10^2$, W/(m·°K)	2.20	2.36	2.51	2.67	2.83	2.90

The methane thermal conductivity coefficient λ_m also depends on the temperature and is taken according to Table 2 or is estimated according to empirical formula

$$\lambda_m = \frac{3.06 + 0.0139 \cdot T}{100} \text{ [W/(m·°K)]} \tag{16}$$

Table 2. The methane thermal conductivity coefficient.

Temperature, °K	240	260	280	300	320	340
$\lambda_m \cdot 10^2$, W/(m ·°K)	2.64	2.88	3.13	3.42	3.72	4.02

In expressions (15) and (16) T is the MAM logarithmic mean temperature which is defined according to formula (Alabiev 2006)

$$T = T_0 + \frac{T_i - T_e}{ln \dfrac{T_i - T_0}{T_e - T_0}} , \text{[°C]} \tag{17}$$

Taking into consideration that the MAM consists of a mixture of dry air, water vapour and methane, the MAM density in formula (5) for the MAM temperature conductivity coefficient estimation can be defined according to the following recommendations (Chernichenko & Podgorniy 2003)

$$\rho = (1-\psi) \cdot (\rho_a + \rho_v) + \psi \rho_m , \text{[kg/m}^3\text{]} \tag{18}$$

where ρ_a – dry air density; ρ_v – water vapour density; ρ_m – methane density.

The densities of dry air, water vapour and methane are estimated according to formulas

$$\rho_a = 3.488 \cdot \frac{P - \varphi \cdot P_p}{T + 273} , \text{[kg/m}^3\text{]} \tag{19}$$

$$\rho_v = 2.168 \cdot \varphi \cdot \frac{P_p}{T + 273} , \text{[kg/m}^3\text{]} \tag{20}$$

$$\rho_m = 1.928 \cdot \frac{P}{T + 273} , \text{[kg/m}^3\text{]} \tag{21}$$

where φ – MAM relative humidity, unit fraction; P – MAM absolute pressure in the gas pipeline, kPa; P_p – partial pressure of saturated steams at MAM average temperature which is defined based on the reference literature or empirical dependence

$$P_p = 0.516 \cdot E^{0.0591 \cdot T} , \text{[kPa]} \tag{22}$$

MAM absolute pressure in the gas pipeline can be calculated from the formula

$$P = P_0 + P_m , \text{[kPa]} \tag{23}$$

where P_0 – atmospheric pressure, kPa; P_m – MAM pressure in the gas pipeline, kPa.

The estimation of MAM specific heat per unit mass in expression (5) is done according to formula, J/(kg·°K) (Federal Standard of Ukraine 2002)

$$c = \frac{(1-\psi)\cdot \rho_a \cdot c_a + \psi \cdot \rho_m \cdot c_m}{\rho}, \tag{24}$$

where c_a – specific heat per unit mass of moist air, J/(kg·°K); c_m – specific heat per unit mass of humid air of methane, J/(kg·°K).

The specific heat per unit mass of moist air is defined

$$c_a = 1005 + 1880 \cdot d_a, \tag{25}$$

$$d_a = 0.622 \cdot \varepsilon \cdot \frac{\varphi \cdot P_p}{P - \varphi \cdot P_p}, \tag{26}$$

where d_a – humidity of moist air, kg/kg; ε – correction factor of methane concentration evaluation in MAM taken from Table 3 (Chernichenko & Podgorniy 2003).

Table 3. Correction factor of methane concentration evaluation in MAM.

Methane content in MAM, %	Correction factor	Methane content in MAM, %	Correction factor
25	1.20	60	1.48
30	1.24	65	1.52
35	1.28	70	1.56
40	1.32	75	1.61
45	1.36	80	1.65
50	1.40	85	1.69
55	1.44	90	1.73

For engineering evaluation an empirical relationship has been obtained to estimate the correction factor which accounts for the methane content in MAM

$$\varepsilon = 0.99 + 0.82 \cdot \psi. \tag{27}$$

The specific heat per unit mass of methane in formula (16) is defined according to Table 4 (Zacheruchenko & Zhuravliov 1969) or is estimated using the empirical formula

$$c_m = 2170 + 2.8 \cdot T. \tag{28}$$

Table 4. The specific heat per unit mass of methane.

Temperature, °K	255	273	298	300	323	373
c_m, kJ/(kg·°K)	2.14	2.17	2.23	2.23	2.29	2.44

The equivalent Nusselt number in formula (11) is estimated by formula (Mikheev & Mikheeva 1973)

$$Nu = \frac{k}{\lambda} d. \tag{29}$$

According to (Mikheev & Mikheeva 1973), in the process of heat interchange between the gas flow and the inner surface of the pipe, the Nusselt number is equal to

$$Nu_g = 0.021 \cdot Re^{0.80} \cdot Pr^{0.43} \cdot \left(\frac{Pr}{Pr_T}\right)^{0.25}, \tag{30}$$

where Pr_T – Prandtl number at the MAM temperature equal to the pipe inner surface temperature.

Taking into account the fact that $Pr/Pr_T \approx 1$ for the air, formula (30) assumes the form

$$Nu_g = 0.021 \cdot Re^{0.80} \cdot Pr^{0.43}. \tag{31}$$

During the pipeline filling with atmospheric air, the Nusselt number is (Mikheev & Mikheeva 1973)

$$Nu_a = 0.245 \cdot Re_a^{0.60}, \tag{32}$$

$$Re_a = \frac{u_a \cdot d}{\nu_a}, \tag{33}$$

where u_a and ν_a – velocity and kinetic viscosity of the atmospheric air (wind).

Formula (33) refers to cases of the strongest heat exchange when the wind blows crosswise. Using (31) and (32) we define the value of the equivalent Nusselt number. It follows from (29) that

$$\alpha_g = \frac{\lambda}{d} Nu_g; \ \alpha_a = \frac{\lambda_a}{d} Nu_a, \tag{34}$$

where λ_a – thermal conductivity coefficient of the atmospheric air, W/(m·K).

After the substitution of (34) for (6) we have

$$k = \frac{1}{\frac{d}{\lambda}\frac{1}{Nu_g} + \frac{\delta}{\lambda_T} + \frac{d}{\lambda_a}\frac{1}{Nu_a}} =$$

$$\frac{\lambda}{d} \frac{Nu_g}{1 + \frac{\lambda}{\lambda_T}\frac{\delta}{d} Nu_g + \frac{\lambda}{\lambda_a}\frac{Nu_g}{Nu_a}}, \tag{35}$$

and according to (29)

$$Nu = \frac{Nu_g}{1 + \frac{\lambda}{\lambda_t} \cdot \frac{\delta}{d} Nu_g + \frac{\lambda}{\lambda_a} \cdot \frac{Nu_g}{Nu_a}}, \tag{36}$$

where Nu_g – Nusselt number for MAM; λ_t – equivalent thermal conductivity coefficient of the pipeline, W/(m·°K); δ – equivalent wall thickness of the pipe, m; λ_a – thermal conductivity coefficient of the atmospheric air, W/(m ·°K); Nu_a – Nusselt number for the atmospheric air.

The equivalent wall thickness of the pipe is defined using the formula

$$\delta = \delta_0 + \delta_i \text{ , [m]} \tag{37}$$

where δ_0 – wall thickness of the pipe, m; δ_i – insulation thickness, m.

The equivalent of thermal conductivity coefficient of the pipeline is estimated by the formula

$$\lambda_t = \frac{\lambda_0 \cdot \delta_0 + \lambda_i \cdot \delta_i}{\delta_0 + \delta_i} \text{ , [W/(m·°K)]} \tag{38}$$

where λ_0 – thermal conductivity coefficient of the pipeline, W/(m·°K); λ_i – insulation thermal conductivity coefficient, W/(m·K).

The thermal conductivity coefficient of the atmospheric air is taken from Table 1 or is estimated from the formula

$$\lambda_a = \frac{2.44 + 0.0078 \cdot T_a}{100} \text{ [W/(m·°K)]} \tag{39}$$

The Nusselt number for MAM in expression (36) is calculated by the formula (Alabiev 2006)

$$Nu_g = 0.0237 \cdot Re^{0.80} , \tag{40}$$

where Re – Reynolds number for MAM.

The estimation of the Reynolds number is done using the formula

$$Re = \frac{u \cdot d}{\nu} , \tag{41}$$

where ν – kinematic viscosity coefficient of MAM. It is taken from Table 5 (Federal Standard of Ukraine 2002) or is estimated from the empirical formula

$$\nu = (17.44 + 0.06 \cdot T - 0.038 \cdot P) \cdot 10^{-6} . \tag{42}$$

The Nusselt number for the atmospheric air in expression (36) is estimated using the formula

$$Nu_a = 0.245 \cdot Re_a^{0.6} , \tag{43}$$

where Re_a – Reynolds number for the atmospheric air defined from the formula

$$Re_a = \frac{\omega \cdot d}{\nu_a} , \tag{44}$$

where ω – atmospheric air velocity, m/s; ν_a – kinematic viscosity of the atmospheric air. It is taken from Table 6 (Federal Standard of Ukraine 2002) or is estimated from the empirical formula

$$\nu_a = (13.36 + 0.092 \cdot T_a) \cdot 10^{-6} \text{ [m}^2\text{/s]} \tag{45}$$

Table 5. MAM kinematic viscosity coefficient, $\nu \cdot 10^6$.

Temperature, °K	Pressure, kPa			
	100	200	400	600
240	11.43	5.73	2.87	1.92
250	12.35	6.19	3.10	2.08
260	13.29	6.66	3.34	2.23
270	14.26	7.14	3.58	2.39
280	15.26	7.65	3.83	2.56
290	16.29	8.15	4.08	2.73
300	17.33	8.67	4.34	2.90
310	18.41	9.21	4.61	3.08
320	19.54	9.77	4.89	3.26
330	20.65	10.35	5.17	3.46
340	21.80	10.91	5.46	3.65
350	22.96	11.49	5.75	3.84

Table 6. The kinematic viscosity coefficient of the atmospheric air.

Temperature, °C	$\nu_a \cdot 10^6$	Temperature, °C	$\nu_a \cdot 10^6$
–30	10.8	30	16.00
–20	12.79	40	16.96
–10	12.43	50	17.95
0	13.28	60	18.97
10	14.16	70	20.02
20	15.06	80	21.09

3 CONCLUSIONS

Methods of estimating the preassembled length of the gas pipeline whose inner surface is ice free while transporting wet firedamp extracted with mine-gas-drainage systems have been worked out. The methods can be used by engineering technicians while designing mine gas pipeline systems which will allow increasing the operation and maintenance safety in winter time.

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