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Theoretical investigation of the temperature regime and pressure distribution in a gas main

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Abstract—A theoretical expression is obtained for a variable temperature and pressure of a real gas moving along a gas main in the presence of heat transfer.

THE GAS dynamic relations will be derived which take into account the real properties of a gas moving in a gas main and heat conduction to the ground. First, some relations will be written which will be required to simplify manipulations in the application to gas mains.

The change of pressure in a pipe-line is given by [1]

$$p = (Z)_{p,T}\frac{k+1}{2k}\frac{1}{\xi_{cr}^2}a_{cr}\left(1-\frac{k_T-1}{k_T}\frac{k}{k+1}\frac{1}{\bar{\eta}}\xi_{cr}^2\lambda^2\right)\frac{1}{\lambda}$$
$$\times\left\{1+\frac{1}{\bar{\eta}}\frac{k_T-1}{k_T}[(Z)_{p,T}-(Z)_{p_0,T}]\right\}^{-1}$$
$$\times\frac{(Z)_{p_0,T_0}}{(Z_1)_{cr}}\rho_0 a_{1cr}q_1\left(1-\frac{1}{\bar{\eta}}\frac{k_T-1}{k_T}\frac{k}{k+1}\xi_{1cr}^2\right)^{1/(k_T-1)}$$
$$\times\left\{1+\frac{1}{\bar{\eta}}\frac{k_T-1}{k_T}[(Z_1)_{cr}-(Z)_{p_0,T_0}]\right\}^{-1/(k_T-1)}. \quad (1)$$

The reduced gas flow rate is [1]

$$q_1 = \frac{G}{F}\times\left\{\frac{1+\frac{1}{\bar{\eta}}\frac{k_T-1}{k_T}[(Z_1)_{cr}-(Z)_{p_0,T_0}]}{1-\frac{1}{\bar{\eta}}\frac{k_T-1}{k_T}\frac{k}{k+1}\xi_{1cr}^2}\right\}^{1/(k_T-1)}$$
$$\times\frac{(Z_1)_{cr}}{\xi_{1cr}\sqrt{\left(2\frac{k}{k+1}p_0(Z)_{p_0,T_0}\rho_0\right)}}. \quad (2)$$

The energy equation has the form [3]

$$\frac{\bar{\eta}}{\omega}\frac{W_{ex}}{G} = \frac{w_2^2-w_1^2}{2}+\int_1^2\left(\frac{\partial f}{\partial p}\right)_T \mathrm{d}p + R\frac{k_T}{k_T-1}\bar{\eta}(T_2-T_1) \quad (3)$$

where W_{ex} is the supplied heat power, $G = \rho(\pi D^2/4)W$ the mass flow rate, D the pipe-line diameter, and w the gas velocity.

The correcting factor is given by [3]

$$\xi_{cr}^2 = y_{cr}^2\frac{k+1}{2}\left[\!\left[1+\frac{1}{\eta}\frac{k_T-1}{k_T}\times\left\{\frac{k}{2}y_{cr}^2-[(Z)_{p_{0cr},T_{cr}}-(Z)_{p_{cr},T_{cr}}]\right\}\right]\!\right]^{-1}. \quad (4)$$

The critical velocity of the real gas is [3]

$$a_{cr} = \xi_{cr}\sqrt{\left(2\frac{k}{k+1}RT_0\right)} \quad (5)$$

$$y_{cr}^2 = \frac{Z_{cr}^2}{k\left(\eta_{cr}-R\frac{\omega_{cr}}{C_{p_{cr}}}\right)}. \quad (6)$$

First of all, it should be noted that equations (1), (2) and (5) can be simplified because of the negligibly small quantity within the square brackets multiplied by the small quantity

$$\left(\frac{1}{\bar{\eta}}-\frac{k_T-1}{k_T}\right).$$

Moreover, the ratio $(Z)_{p_0,T_0}/(Z_1)_{cr}$ in equation (1) can be taken approximately equal to unity.

As a result, the following expressions can be obtained for gas mains:

$$p = (Z)_{p,T}\frac{k+1}{2k}\frac{1}{\xi_{cr}^2}a_{cr}\left(1-\frac{k_T-1}{k_T}\times\frac{k}{k+1}\frac{1}{\bar{\eta}}\xi_{cr}^2\lambda^2\right)\frac{1}{\lambda}\rho_0 a_{1cr}q_1\left(1-\frac{1}{\bar{\eta}}\frac{k_T-1}{k_T}\times\frac{k}{k+1}\xi_{cr}^2\right)^{1/(k_T-1)} \quad (7)$$

NOMENCLATURE

a	speed of sound in real gas [m s^{-1}]	T	temperature [K]
a_{cr}	critical velocity of real gas [m s^{-1}]	w	gas velocity [m s^{-1}]
a_{id}	speed of sound in ideal gas [m s^{-1}]	y	correction factor, a/a_{id}
$(a_{cr})_{id}$	critical velocity of ideal gas [m s^{-1}]	Z	coefficient of compressibility.
C_p	isobaric heat capacity of real gas [J kg^{-1} K^{-1}]		
F	tube cross-section [m^2]	Greek symbols	
G	gas flow rate [kg s^{-1}]	ξ	correction factor
k	specific heat ratio of ideal gas, C_p/C_v	ξ_{cr}	$a_{cr}(a_{cr})_{id}$
k_T	temperature index of real gas adiabatic, $[1-(p/T)(\partial T/\partial p)_s]^{-1}$	ρ	density [kg m^{-3}].
p	pressure [N m^{-2}]	Subscripts	
R	gas constant [J kg^{-1} K^{-1}]	cr	critical
		id	ideal.

$$q_1 = \frac{G}{F}\left(1-\frac{1}{\bar{\eta}}\frac{k_T-1}{k_T}\frac{k}{k+1}\xi_{1cr}^2\right)^{-1/(k_T-1)} \times \frac{(Z_1)_{cr}}{\xi_{1cr}\sqrt{\left(2\frac{k}{k+1}p_0(Z)_{p_0,T_0}\rho_0\right)}} \quad (8)$$

$$\xi_{cr}^2 = y_{cr}^2\frac{k+1}{2}\left(1+\frac{1}{\bar{\eta}}\frac{k_T-1}{k_T}\frac{k}{2}y_{cr}^2\right)^{-1}. \quad (9)$$

Equation (3) can be written in differential form as

$$\frac{\bar{\eta}}{\bar{\omega}}\frac{dW_{ex}}{G} = \frac{dw^2}{2} + \left(\frac{\partial f}{\partial p}\right)_T dp + R\frac{k_T}{k_T-1}\bar{\eta}\,dT. \quad (10)$$

Since $\omega = (C_p/R)((k_T-1)/k_T)$ [3]

$$\frac{\bar{\eta}}{\bar{\omega}}\frac{dW_{ex}}{G} = \frac{dw^2}{2} + \left(\frac{\partial f}{\partial p}\right)_T dp + \frac{\bar{\eta}}{\bar{\omega}}C_p\,dT. \quad (11)$$

Taking into account the Joule–Thomson effect, which will be denoted by J(°C g m^{-1}), equation (11) can be rewritten as

$$\frac{\bar{\eta}}{\bar{\omega}}\frac{dW_{ex}}{G} = \frac{dw^2}{2} + \left(\frac{\partial f}{\partial p}\right)dp + \frac{\bar{\eta}}{\bar{\omega}}C_p(dT + J\,dl) \quad (12)$$

where dl is the length of the tube element.

Integrating equation (12) yields

$$\frac{\bar{\eta}}{\bar{\omega}}\frac{W_{ex}}{G} = \frac{w_2^2-w_1^2}{2} + \int_1^2\left(\frac{\partial f}{\partial p}\right)_T dp + \frac{\bar{\eta}}{\bar{\omega}}C_p(T_2-T_1) + \frac{\bar{\eta}}{\bar{\omega}}C_pJ\int_0^l dl. \quad (13)$$

In view of the fact that gas cools down in the course of its motion in a gas main, equation (13) can be written as

$$\frac{\bar{\eta}}{\bar{\omega}}\frac{W_{ex}}{G} - \frac{\bar{\eta}}{\bar{\omega}}C_pJ\int_0^l dl = \frac{w_1^2-w_2^2}{2} + \int_1^2\left(\frac{\partial f}{\partial p}\right)dp + \frac{\bar{\eta}}{\bar{\omega}}C_p(T_1-T_2). \quad (14)$$

It was suggested in refs. [3, 4] that

$$\int_1^2\left(\frac{\partial f}{\partial p}\right)_T dp = RT_1[(Z_2)_{T_1} - (Z_1)_{T_1}]. \quad (15)$$

Substituting equation (15) into equation (14) and writing out the latter in the application to the critical regime, as well as assuming the finite parameters to be variable, it is possible to obtain

$$\frac{\bar{\eta}}{\bar{\omega}}\left(\frac{W_{ex}}{G} - C_pJ\int_0^l dl\right) = \frac{a_{1cr}^2 - a_{cr}^2}{2} + RT_{1cr} \times [(Z_{cr})_{T_{1cr}} - (Z_{1cr})_{T_{1cr}}] + \frac{\bar{\eta}}{\bar{\omega}}C_p(T_1-T_2). \quad (16)$$

By virtue of equation (4) obtain

$$a_{1cr}^2 = 2\xi_{1cr}^2\frac{k}{k+1}RT_0 \quad (17)$$

$$a_{cr}^2 = 2\xi_{cr}^2\frac{k}{k+1}RT_{0x} \quad (18)$$

where T_0 is the gas stagnation temperature at the inlet to a pipe-line, and T_{0x} the variable (because of cooling) gas stagnation temperature.

It is possible to write that

$$a_1^2 = y_1^2kRT_1, \quad a^2 = y^2kRT.$$

When $M = 1$

$$a = a_{cr}, \quad a_1 = a_{1cr}.$$

Substituting the values of the temperatures expressed in terms of the critical velocities into equation (16) gives

$$\frac{\bar{\eta}}{\bar{\omega}}\left(\frac{W_{ex}}{G}-C_pJ\int_0^l \mathrm{d}l\right) = \frac{a_{1cr}^2-a_{cr}^2}{2}+\frac{a_{1cr}^2}{ky_{1cr}^2}[(Z_{cr})_{T_{1cr}}-(Z_{1cr})_{T_{1cr}}] + \frac{\bar{\eta}}{\bar{\omega}}C_p\left(\frac{a_{1cr}^2}{kRy_{1cr}^2}-\frac{a_{cr}^2}{kRy_{cr}^2}\right)$$

or, with regard for equations (17) and (18)

$$\frac{\bar{\eta}}{\bar{\omega}}\left(\frac{W_{ex}}{G}-C_pJ\int_0^l \mathrm{d}l\right) = a_{1cr}^2\left\{\frac{1}{2}+\frac{1}{ky_{1cr}^2}\times[(Z_{cr})_{T_{1cr}}-(Z_{1cr})_{T_{1cr}}]+\frac{\bar{\eta}}{\bar{\omega}}\frac{C_p}{Ry_{1cr}^2k}\right\} - a_{cr}^2\left(\frac{1}{2}\frac{\bar{\eta}}{\bar{\omega}}\frac{C_p}{Rky_{cr}^2}\right). \quad (19)$$

Neglecting, because of the small size, the quantity

$$\frac{1}{ky_{1cr}^2}[(Z_{cr})_{T_{1cr}}-(Z_{1cr})_{T_{1cr}}]$$

equation (19) can be written in the form

$$\frac{\bar{\eta}}{\bar{\omega}}\left(\frac{W_{ex}}{G}-C_pJ\int_0^l \mathrm{d}l\right) = a_{1cr}^2\left(\frac{1}{2}+\bar{\eta}\frac{C_p}{\omega}\frac{1}{ky_{1cr}^2R}\right) - a_{cr}^2\left(\frac{1}{2}+\frac{\bar{\eta}}{\bar{\omega}}\frac{C_p}{Rky_{cr}^2}\right). \quad (20)$$

Introducing

$$\omega = \frac{C_p}{R}\frac{k_T-1}{k_T}$$

into equation (20) and taking into account equation (9) results in

$$\frac{\bar{\eta}}{\bar{\omega}}\left(\frac{W_{ex}}{G}-C_pJ\int_0^l \mathrm{d}l\right) = RT_0ky_{1cr}^2 \times\left[\frac{1}{2}+\bar{\eta}R\left(\frac{k_T}{k_T-1}\right)_1\frac{1}{ky_{1cr}^2R}\right] \times\left[1+\frac{1}{\bar{\eta}}\left(\frac{k_T-1}{k_T}\right)_1\frac{k}{2}y_{1cr}^2\right]^{-1} - RT_{0x}ky_{cr}^2\left[\frac{1}{2}+\bar{\eta}R\left(\frac{k_T}{k_T-1}\right)_X\frac{1}{ky_{cr}^2R}\right] \times\left[1+\frac{1}{\bar{\eta}}\left(\frac{k_T-1}{k_T}\right)_X\frac{k}{2}y_{cr}^2\right]^{-1}. \quad (21)$$

Here, the quantity $(k_T-1)/k_T$ has been given the subscript X which indicates that it is a variable quantity because of gas cooling in the pipe-line and that it corresponds to the variable stagnation temperature T_{0x}.

After transformations equation (21) can be presented in the form

$$T_0\left(\frac{k_T}{k_T-1}\right)_1\bigg/\left(\frac{k_T}{k_T-1}\right)_X - T_{0x} = \left[\left(\frac{k_T-1}{k_T}\right)_{av}\times\left(\frac{k_T}{k_T-1}\right)_X\right]^{-1}\left(\frac{W_{ex}}{GC_p}-V\int_0^l \mathrm{d}l\right). \quad (22)$$

Having introduced the notation

$$A = \left(\frac{k_T}{k_T-1}\right)_{av}\left(\frac{k_T-1}{k_T}\right)_X \quad (22')$$

$$B = \left(\frac{k_T}{k_T-1}\right)_1\bigg/\left(\frac{k_T}{k_T-1}\right)_X = \left(\frac{k_T}{k_T-1}\right)_1\left(\frac{k_T-1}{k_T}\right)_X \quad (22'')$$

$$\theta = \frac{A}{B} = \left(\frac{k_T}{k_T-1}\right)_{av}\left(\frac{k_T-1}{k_T}\right)_1$$

$$\left(\frac{k_T}{k_T-1}\right)_{av} = \frac{1}{2}\left[\left(\frac{k_T}{k_T-1}\right)_1+\left(\frac{k_T}{k_T-1}\right)_2\right] \quad (22''')$$

(where subscript 2 refers to the gas parameters at the end of the pipe-line element considered), equation (22) can be rewritten as

$$BT_0-T_{0x} = \theta\left(\frac{W_{ex}}{GC_p}-J\int_0^l \mathrm{d}l\right). \quad (23)$$

The heat conducted from the gas to the ground along the pipe-line element is determined as

$$W_{ex} = -\pi D\int_0^l K(T-T_{gr})\,\mathrm{d}l \quad (24)$$

where K is the coefficient of heat conduction from the gas to the ground, T_{gr} the ground temperature in Kelvin, and D the pipe-line diameter.

Substituting equation (24) into equation (23) yields

$$BT_0-T_{0x} = -\theta\left[\int_0^l \frac{\pi DK}{GC_p}(T-T_{gr})+J\right]\mathrm{d}l.$$

Using the notation

$$C = \frac{\pi DK}{GC_p} \quad \text{and} \quad T' = T_{gr}-\frac{J}{C}$$

it is possible to write

$$BT_0-T_{0x} = -\theta\int_0^l C(T_{0x}-T')\,\mathrm{d}l. \quad (25)$$

For the integration of equation (25), the following numbers are used:

$$Nu = \frac{KD}{\lambda_T} \quad (26)$$

$$Pr = \frac{\nu C_p\rho}{\lambda_T} \quad (27)$$

$$Re = \frac{\bar{w}D}{\nu}. \tag{28}$$

(Since the heat flows across thin tubes it is possible to assume that $K \approx \alpha$, i.e. to the heat transfer coefficient in the expression for the Nusselt number; subscript T in the thermal conductivity coefficient λ_T is used to distinguish it from the velocity coefficient λ.)

The weight flow rate is

$$G = \rho \frac{\pi D^2}{4} w. \tag{29}$$

The simultaneous solution of equations (26)–(28) will give the quantity C in terms of the above numbers and pipe-line diameter as

$$C = \frac{4Nu}{D\, Pr\, Re}. \tag{30}$$

Substituting equation (30) into equation (25) gives

$$BT_0 - T_{0x} = -\theta \int_0^l \left[\frac{\pi DK}{GC_p}(T_{0x} - T')\right] \mathrm{d}l. \tag{31}$$

It is seen from equation (30) that the quantity C depends on Nu, Re, Pr and D. These numbers vary little along a constant-diameter pipe-line. This allows C to be considered as a constant in integration. Also constant is the quantity θ expressed by equation (22‴).

Now, equation (31) can be presented as

$$\frac{\mathrm{d}T_{0x}}{T_{0x} - T'} = -\theta C\, \mathrm{d}l. \tag{32}$$

Integration gives

$$\ln(T_{0x} - T') = \theta Cl + \text{const}. \tag{33}$$

The integration constant is determined taking into account that

$$l = 0, \quad T_{0x} = BT_0.$$

Thus

$$\frac{T_{0x} - T'}{BT_0 - T'} = \mathrm{e}^{-\theta Cl}. \tag{34}$$

By virtue of the fact that

$$T' = T_{gr} - J/C \tag{35}$$

equation (34) can be written as

$$\frac{T_{0x} - T_{gr} + \dfrac{J}{C}}{BT_0 - T_{gr} + \dfrac{J}{C}} = \mathrm{e}^{-\theta Cl}. \tag{36}$$

Whence there results the expression for the variable stagnation temperature

$$T_{0x} = (BT_0 - T_{gr})\,\mathrm{e}^{-\theta Cl} + T_{gr} - \frac{J}{C}(1 - \mathrm{e}^{-\theta Cl}). \tag{37}$$

Equation (36) differs from an analogous expression obtained in ref. [5], because in the present paper the flow of a real gas is considered the non-ideal character of which is taken into account by the coefficients B and θ given in terms of the temperature indices of the real gas adiabatic.

Thus, coefficients B and θ make it possible to take account of a set of important factors that characterize the specific features of a real gas. For an ideal gas $B_{id} = 1$ and $\theta_{id} = 1$. Moreover, equation (36) involves a varying stagnation temperature T_{0x}, whereas the expression given in ref. [5] involves a varying thermodynamic temperature T for a perfect gas flow.

At a certain place in the pipe-line the gas temperature attains the temperature of the ground. This distance from the pipe-line inlet can be determined by assuming that $T_{0x} = T_{gr}$ in equation (37) and also that $B = 1$ at the beginning of the pipe-line. Then, this distance l_x will be determined as

$$l_x = \frac{1}{\theta C} \ln\left[\frac{C}{J}(T_0 - T_{gr}) + 1\right]. \tag{38}$$

Now, the pressure and velocity distributions in a pipe-line will be established.

In ref. [2] the solution of gas dynamic problems in real gas flows in the presence of heat transfer gave the following important expression:

$$\left(1 - \frac{1}{\bar{\eta}}\xi_{cr}^2 \frac{k_T - 1}{2k_T} - \frac{k+1}{2k}\frac{1}{\lambda^2}\right)\frac{\mathrm{d}\lambda}{\lambda} + \left(1 - \frac{1}{\bar{\eta}}\xi_{cr}^2 \frac{k_T - 1}{2k_T} + \frac{k+1}{2k}\frac{1}{\lambda^2}\right)\mathrm{d}\ln\frac{a_{cr}}{a_{1cr}} = -\zeta\frac{\mathrm{d}l}{2D}. \tag{39}$$

In the first approximation, assuming the gas to be ideal and heat transfer to be absent, the following relation can be used which is well known in gas dynamics:

$$\frac{1}{\lambda_{1id}^2} - \frac{1}{\lambda_{2id}^2} - \ln\frac{\lambda_{2id}^2}{\lambda_{1id}^2} = \frac{2k}{k+1}\zeta\frac{l}{D}. \tag{40}$$

Under the same assumptions, the reduced flow rate of the ideal gas is given by

$$q_{1id} = \frac{G}{Fp_{01}}\left(\frac{k+1}{2}\right)^{1/(k-1)}\left(\frac{2k}{k+1}\frac{1}{RT_{01}}\right)^{1/2}. \tag{41}$$

From the prescribed values of G, F, p_{01} and T_{01} it is possible to find q_{1id} and then λ_{1id} from the tables of gas dynamic functions.

Taking the quantity λ_{2id} in equation (40) to be the velocity coefficient at an arbitrary section of the pipe, it is possible to find, in the first approximation, the distribution of λ_{id} along the pipe. Provided the stagnation temperature is constant, equation (2) will give the following well-known expression, in the first approximation, for the pressure distribution along a pipe for the ideal gas in the absence of heat transfer

$$p_{\rm id} = \left(\frac{2}{k+1}\right)^{1/(k-1)} \rho_{01} q_{1\rm id} \frac{1}{\lambda_{\rm id}} \left(1 - \frac{k-1}{k+1}\lambda_{\rm id}^2\right). \quad (42)$$

Knowing in the first approximation the distribution of $\lambda_{\rm id}$ along a pipe-line, it is possible to determine from equation (42) the pressure distribution throughout the pipe-line. Then from these pressures and temperature variations, determined by equation (37), it is possible to find the quantities Z, ω, η, k_T, y, and $\xi_{\rm cr}$, which depend on pressure and temperature. These quantities are determined in the following order.

In the literature the compressibility factor Z is usually determined from the Berthelot state equation. However, this equation becomes inaccurate for pressures above 50 bar. In this case it is more advisable to determine Z from the experimental diagrams of compressibility.

The expressions for ω and η are given in ref. [6]

$$\eta = Z - p\left(\frac{\partial Z}{\partial p}\right)_T \quad (43)$$

$$\omega = Z + T\left(\frac{\partial Z}{\partial T}\right)_p. \quad (44)$$

The partial derivatives $(\partial Z/\partial p)_T$ and $(\partial Z/\partial T)_p$ in these equations are determined by the method of graphical differentiation.

The coefficient y was obtained in ref. [1] and has the form

$$y = \frac{Z}{\sqrt{\left(k\left(\eta - \frac{R}{C_p}\omega\right)\right)}}. \quad (45)$$

The coefficient $\xi_{\rm cr}$ is found from equation (4), with y being determined at critical parameters.

The temperature index of the adiabatic k_T can be found from the expression [7]

$$\omega = \frac{C_p}{R}\frac{k_T - 1}{k_T}. \quad (46)$$

On having determined $\xi_{1\rm cr}$ and $\xi_{\rm cr}$, the value of $a_{1\rm cr}$ is determined from the values of T_{0x} found from equation (37), as well as different values of $a_{\rm cr}$ for each T_{0x} along the gas pipe-line.

Finally, to determine the pressure distribution in a real gas with allowance for heat transfer by formula (2), it is necessary to know λ. As the values of $a_{\rm cr}$ are now available, it is possible to determine λ from equation (39) with the aid of a computer.

CALCULATION OF THE TEMPERATURE REGIME AND COMPARISON OF THE RESULTS OBTAINED WITH EXPERIMENTAL DATA

In the example given in ref. [7] the pipe-line has a length of 128 km and a diameter of 760 mm. The gas flow rate is 0.58×10^6 kg h^{-1} and the initial gas pressure is 30.6 kg cm^{-2}. The ground temperature is $t_{\rm gr} = 16.7$°C. The heat transfer coefficient is taken to be 2.44 kcal m^{-2} h^{-1} K^{-1}.

In Table 1 the experimental data of Shorre are presented as well as the computational results of other authors. These data are supplemented with results on gas temperature variations along a gas main obtained theoretically in the present work.

For the given initial and final pressures use can be made of the Berthelot state equation in which

$$Z = 1 + \frac{9}{128}\frac{p}{p_c}\frac{T_c}{T}\left(1 - 6\frac{T_c^2}{T^2}\right) \quad (47)$$

where $p_c = 44.9$ atm, $T_c = 190.5$ K.

With the partial derivatives $(\partial Z/\partial p)_T$ and $(\partial Z/\partial T)_p$ being found from equation (47), equation (4) gives that $\eta = 1$, whereas

$$\omega = 1 + \frac{27}{32}\frac{p}{p_c}\frac{T_c^3}{T^3}. \quad (48)$$

In the data given for the pipe-line: $\omega_1 = 1.2$; $\omega_2 = 1.16$. With the heat capacity $C_p = 2.219$ kJ kg^{-1} K^{-1}, equation (46) gives

$$\left(\frac{k_T - 1}{k_T}\right)_1 = 0.281; \quad \left(\frac{k_T - 1}{k_T}\right)_2 = 0.272;$$

$$\left(\frac{k_T - 1}{k_T}\right)_{\rm av} = 0.276.$$

According to equation (22‴), $\theta = 1.016$. According to equation (22″), B is a variable quantity, which changes very little along the pipe-line. The values of B are presented in Table 1.

The quantity C, which enters into computational formula (37) and which is defined as $C = (\pi DK)/(GC_p)$, depends on the heat conduction coefficient K. Allowing for the conducting properties of the surrounding ground, Shukhov and Leibenzon [7] recommended that for moist sand this coefficient should be taken equal to $K = 3$ kcal m^{-2} h^{-1} K^{-1} [5]. At the given values for the gas pipe-line, when $K = 3$, the value of $C = 2.33 \times 10^{-5}$ m^{-1}. The Joule–Thomson effect constitutes $J = 6.2 \times 10^{-5}$ g m^{-1}, $T_0 = 327.4$ K. In Shorre's calculations $K = 2.44$ kcal m^{-2} h^{-1} K^{-1}.

Thus, entering all the values into equation (37) the value of T_{0x} along the gas pipe-line can be determined. The values found are included in Table 1. As is seen from Table 1, the values of T_{0x} agree rather well with the data measured experimentally by Shorre. The table contains thermodynamic temperatures T instead of the stagnation temperatures T_{0x}. But as the gas velocities in the pipe-line are small the values of T_{0x} do not virtually differ from those of T.

According to formula (38), $l_x = 115\,000$ m. At the values of K and C used by Shorre, $l_x = 110\,000$ m. Equation (37) gives for $l \to \infty$ [5]

Table 1

l/L	Value of B in formula (37)	t (°C) By formula (37)	According to Shorre's experimental data	By Shukhov's formula	According to data obtained in ref. [6]
0.125	0.996	40.9	40.5	43.6	43.4
0.175	0.994	36.9	37.8	40.6	40.2
0.312	0.990	28.6	31.7	33.5	32.2
0.586	0.981	20.8	21.1	24.9	21.4
0.750	0.976	17.4	16.7	21.9	18.0
1.000	0.968	15.5	12.8	19.0	15.2

$$(T_{0x})_{\min} = T_{gr} - \frac{J}{C}.$$

In the case considered in the present paper

$$(t_{0x})_{\min} = 16.7 - \frac{6.2}{2.33} = 14°\text{C}.$$

This is found to be close to the experimental data of Shorre, because Shorre's experimental values of l_x

$$(t_{0x})_{\min} = 16.7 - \frac{6.2}{2.5} = 14.3°\text{C}.$$

CONCLUSIONS

(1) It is evident from Table 1 that the allowance for the nonideality of the gas is very important for finding the temperature distribution along a gas main.

(2) The formula suggested by Shukhov relates to the ideal gas flow. Therefore, the temperatures by this formula deviate greatly from those obtained in Shorre's experiments.

(3) Since the results are very sensitive to the heat conduction coefficient, its correct selection with regard for the ground conditions is very important.

(4) It is seen from Table 1 that in both the present work and ref. [7] the allowance for the gas nonideality brings about the gas temperature decrease below the ground temperature. This fact requires further experimental investigations.

(5) The agreement between the experimental data of Shorre and the results obtained in the present work and in ref. [7] is the result of the allowance for the nonideality of gas moving in a pipe-line. Therefore, the relations obtained can be recommended for practical application.

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ETUDE THEORIQUE DE LA DISTRIBUTION DE TEMPERATURE ET DE PRESSION DANS UN GAZODUC

Résumé—On obtient une expression théorique pour la température variable et la pression d'un gaz s'écoulant dans un gazoduc en présence d'un transfert thermique.

THEORETISCHE UNTERSUCHUNG VON TEMPERATUR- UND DRUCKVERTEILUNG IN EINER GAS-HAUPTLEITUNG

Zusammenfassung—Eine theoretische Formulierung für die variablen Werte von Temperatur und Druck eines realen Gases, das unter dem Einfluß von Wärmeübertragung in einer Gas-Hauptleitung strömt, wird vorgestellt.

ТЕОРЕТИЧЕСКОЕ ИССЛЕДОВАНИЕ ТЕМПЕРАТУРНОГО РЕЖИМА, А ТАКЖЕ РАСПРЕДЕЛЕНИЯ ДАВЛЕНИЯ В МАГИСТРАЛЬНОМ ГАЗОПРОВОДЕ

Аннотация—На основе теоретических исследований получено аналитическое выражение переменной температуры и давления реального газа, движущегося вдоль газопровода при наличии теплообмена.