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Natural Gas Pipeline Transportation as the Thermodynamic Process

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Abstract: A verification of commonly used approval in pipeline hydraulics is carried out that the work of friction forces performed at the movement of real gas on the gas pipeline completely turns into thermal energy. It is obvious that measurements of the actual temperature of the transported gas cannot confirm this hypothesis due to the inaccuracy of measurements of parameters affecting thermal processes in a real gas pipeline. The solution of the initial system of differential equations describing the 1-D process of stationary pipeline transportation of natural gas is considered as a serial set of values of thermobaric and rate flow parameters - pressure, temperature, velocity – of elementary volume of gas as it moves through the gas pipeline, that is, the Lagrangian approach is used in the study of the pipeline natural gas transport process. By means of integral definition of entropy by Clausius it is shown that the mentioned statement about the conversion of the work of the friction forces entirely into the thermal energy of the gas flow finds its confirmation with an accuracy acceptable for engineering applications in relation to the one-dimensional formulation of the problem of determining temperature of a gas along the length of pipeline.

Keywords: Gas Transportation, Gas Pipeline, One–dimensional Model of Flow, Nonequilibrium Thermodynamics, Entropy, Thermal Balance

1. Introduction

When modeling thermal processes in gas pipelines, it is usually assumed that the work of the friction forces produced during the movement of gas through the pipeline is completely converted into thermal energy and is not spent on changing the kinetic energy of the gas flow. It is usually accepted as not requiring proof.

Note that even precision measurements of the temperature of the transported gas would not allow confirming this position due to inaccuracies in the measurements of parameters that affect thermal processes in a real gas pipeline.

In this paper, a method is proposed to verify the validity of this assumption using the equation of the integral definition of entropy.

2. Modeling of Hydraulics and Thermal Modes of Natural Gas Pipeline Transportation Process

The thermobaric and rate flow parameters of the steady-state movement of natural gas through a main gas pipeline with a constant internal diameter are calculated using the following system of one-dimensional differential equations (1)-(3):

$$\frac{d}{dx}(\rho w) = 0, \tag{1}$$

$$\frac{d}{dx}(p+\rho w^2)=-\lambda \frac{\rho|w|w}{2D}-g\rho\beta, \tag{2}$$

$$\frac{d}{dx}\left[h+\frac{w^2}{2}\right]=\frac{4U}{\rho w D}(T_{ext}-T)-g\beta. \tag{3}$$

In the system of equations (1)-(3), the contribution of external work performed on the gas is excluded.

In the momentum conservation equation (2), the first term in the right part - $\lambda \frac{\rho|w|w}{2D}$ is a generalization to the turbulent gas flow regime of the formula for specific friction pressure losses obtained in the framework of the exact solution of the Navier-Stokes equation for one-dimensional laminar flow of a viscous fluid through a pipe [3].

In the general case friction factor λ in accordance with Buckingham's π-theorem depends not only on the Reynolds criterion number, as is the case for laminar gas movement through the pipe, but also on the relative roughness of the inner surface of the pipes.

Considering the process of transporting natural gas as thermodynamic, as closing relations when solving the system of equations (1) - (3), when choosing as independent thermodynamic parameters, pressure p and temperature T, are used thermal equation of state (EoS)

$$\rho=\rho(p,T), \tag{4}$$

and a calorical equation of state in the form of a complete differential of the specific enthalpy

$$dh=c_p(dT-\mu dp). \tag{5}$$

It follows from (3) and (5) that the thermal balance of the gas flows includes contributions of:

1. heat generated by flow throttling;
2. external heat input;
3. thermal equivalents of work on kinetic energy change and on lifting of gas moved through pipeline in gravitational field.

It is important to note that when deriving the energy conversion equation (3), the mentioned assumption was used about the identical equality of the work of the friction forces and the thermal energy emitted inside the gas volume during its transportation.

The system of one-dimensional equations of steady-state gas movement through the pipeline (1) - (3) is obtained on the basis of laws of mass and momentum conservation, transformation of gas flow energy and the first beginning of thermodynamics in relation to the elementary volume of gas moving along the gas pipeline, which has the form of a cylinder with length dx and diameter D, which contacts the pipe wall along the entire lateral surface.

3. Thermodynamic Process of Natural Gas Pipeline Transportation

The elementary volume of a gas, despite its small physical dimensions, contains a sufficiently large number of molecules, so that the laws of statistical physics and thermodynamics can be applied to it, i.e. it can be considered as a thermodynamic system. For example, in a modern high-pressure gas pipeline with an internal diameter of 1 m, the described cylinder with a length of 10 mm can contain up to 10^{11} molecules. A thermodynamic system defined in this way is an open system in which heat exchange is carried out through the side surface with the environment and the exchange of mechanical energy in the end sections. There is no mass transfer in the end sections in accordance with equation (1).

The process of pipeline transportation of gas, taking into account heat exchange with the environment and the work of friction forces, is obviously non-equilibrium and irreversible. However, using the generally accepted approach based on the assumption that the considered elementary volume of gas is in local thermodynamic equilibrium, it is possible to solve the system of equations (1)-(5), assuming that:

1. the thermodynamic state of the elementary gas volume can be fully determined by two intensive thermodynamic parameters - pressure p and temperature T, as well as the component composition of the gas;
2. all quantitative conclusions of classical equilibrium thermodynamics can be applied to the elementary gas volume.

The solution of this system of equations can be described by a sequential set of values of thermobaric and rate flow parameters (pressure, temperature, velocity) of an elementary volume of gas as it moves through the pipeline. This means that from the standpoint of thermodynamics, the gas transportation process is a chain of successive transitions with a time step $\frac{dx}{w}$ of an elementary control volume of gas from the initial equilibrium state (in the initial section of the gas pipeline) to all subsequent equilibrium states in the direction of movement up to the final section of the gas pipeline. A similar manner defined a certain process of gas movement in pipe is based on a Lagrangian approach to the study of the process of pipeline transport of natural gas.

A process consisting of a continuous sequence of equilibrium thermodynamic states refers to equilibrium or quasi-static, which is true only with respect to sufficiently slow processes. Processes close to equilibrium processes are those in which the rates of change of the macroscopic local parameters of the system are much less than the rates of their microscopic relaxation processes bringing the system to local thermodynamic equilibrium. The characteristic times of relaxation processes in gas at pressure and temperature values typical for modern export gas pipelines do not exceed 10^{-4} s [4].

From the above it follows that the system of differential equations (1) - (5) allows, instead of the real process of gas pipeline transportation, to calculate an imaginary equilibrium process of gas transportation and calculate one-dimensional (along the length of the gas pipeline) values of thermobaric and rate parameters.

4. Integral Definition of Entropy by Clausius

The principal possibility of verifying this statement is based on the use of the integral definition of entropy by Clausius: the change in entropy Δs during an irreversible transformation from state in to state out can always be calculated by integrating the parameters of a suitably selected reversible thermodynamic process in which the change in entropy is exclusively due to heat exchange in the thermodynamic system under consideration [5]:

$$\Delta s = s_{out} - s_{in} = \int_{in}^{out} ds. \tag{6}$$

In this paper, when calculating the integral in (6), the quasi-static (equilibrium) process described above is used as a reversible thermodynamic process of gas transport.

Entropy is a function of the state of the thermodynamic system, and its change as a result of the thermodynamic process is determined in the described case by the difference in pressure and temperature of the transported gas in the final and initial sections of the pipeline.

With respect to the gas pipeline process, equation (6) shows the equality of the two calculated values Δs : values of pair of thermobaric parameters (p_{out}, T_{out}) and (p_{in}, T_{in}) of gas pipeline in its final and initial sections respectively and determined as a result of calculation of integral in (6) using solution of system of equations (1) - (5) for selected equilibrium process of gas transport with the same values of thermobaric parameters in final and initial sections.

The total differential of entropy increment of an open thermodynamic system is determined by the sum of two independent differentials

$$ds = ds_e + ds_i, \tag{7}$$

where ds_e and ds_i is a change in the entropy of the elementary volume of gas, caused respectively by the exchange of energy with the environment and an irreversible process in the system itself.

5. Procedure for Verifying the Validity of the Generally Accepted Concept

For the process of pipeline gas transportation, the following explicit expressions are valid for above differentials, containing local values of the measured or calculated thermohydraulic parameters of natural gas transportation.

In equation (7), the differential ds_e is written as

$$ds_e = \frac{\pi d U \left(T_{ext} - T \right)}{GT} dx, \tag{8}$$

and differential ds_i as

$$ds_i = \gamma \lambda \frac{w^2}{2gDT} dx, \tag{9}$$

Here, the factor γ ($0 < \gamma \le 1$) is introduced by us to estimate the part of the work of the friction forces during the movement of the gas flow that passes into thermal energy. The positive certainty of the local values of the entropy increment caused by irreversible processes in a thermodynamic system is one of the formulations of the second principle of thermodynamics introduced by I. Prigogine.

The increments of the entropy of the gas flow along the gas pipeline, given by equations (8) and (9), agree at = 1 with equations (3), (5) and the mechanical energy equation (generalized Bernoulli equation) for the compressible fluid. At 0 < γ < 1, the energy conversion equation (3) can be written as follows:

$$\frac{d}{dx}\left[h + \frac{w^2}{2} \right] = \frac{4U}{\rho w D}\left(T_{ext} - T \right) - \lambda \left(1 - \gamma \right) \frac{w^2}{2D} - g\beta. \tag{10}$$

Equation (9) for the differential ds_{fr} at γ = 1 corresponds to the statement that in 1-D formulation of the problem of the movement of a compressible viscous medium (gas) through a pipeline, the work of the friction forces completely passes into the heat generated inside the control volume [6, 7] and this heat does not participate in the formation of the temperature of the gas flow explicitly. This statement is widely used in the study of thermohydraulics of gas flows in channels (pipes) and significantly simplifies the equation of the balance of thermal energy, with which the longitudinal temperature of the gas is calculated.

Some authors [8] treat the above statement as an assumption, and not as a postulate. As for the general formulation of the problem of the three-dimensional motion of a compressible viscous fluid, the statement is true here (see Russian classical textbook [9]) that when the fluid moves under the action of mass and surface forces, some part of the mechanical energy irreversibly transforms into thermal energy. The magnitude of such energy can be judged only by the results of experimental observations of thermal processes in the system.

Taking into account equations (8) and (9), the integral determination of the entropy change in the appropriately selected equilibrium process of gas movement through the pipeline has the form

$$\Delta s = \int_{in}^{out} \frac{1}{T} \left[\gamma \lambda \frac{w^2}{2gd} + \frac{\pi D U \left(T_{ext} - T \right)}{G} \right] dx. \tag{11}$$

6. Numerical Example

Let's compare the values of the entropy change obtained using the thermal equation of state and numerical calculation of the integral in (10) using an imaginary experiment.

Let's assume that there is information on the parameters and modes of the active main gas pipeline: the length of an almost horizontal gas pipeline is 120 km; the inner diameter of the pipes is 1.38 m; the type of laying is underground; the average ground temperature at the depth of the pipes is – 2°C; daily productivity is 150 million m^3; gas component composition: methane – 96%, ethane – 2.2%, propane − 0.6%, nitrogen – 1.2%: pressure and temperature at the entrance to the gas pipeline – 9.8 MPa and 30°C, pressure and temperature at the outlet of the gas pipeline – 6.23 MPa and 10.5°C.

When calculating the entropy of natural gas of a given composition, the corresponding correlation dependence was applied using Peng–Robinson EoS, which is part of the PIPESIM 9.0 software computing complex. The calculated difference in the values of specific entropy in the final and initial sections of the gas pipeline was 0.136 kJ/kg/K. It follows from this assessment that the entropy of natural gas increases during its transportation through a gas pipeline.

An imaginary reversible gas transport process, which is determined by the solution of a system of equations (1), (2), (10), (4), (5), it was modeled using the calculated thermohydraulic algorithms of the PIPESIM 9.0 complex. The following assumptions were used in the calculations:

1. Peng-Robinson equation is used as the thermal EoS of the gas of a above component composition;
2. equivalent roughness of the pipes is assumed to be equal to 7 microns;
3. coefficient of hydraulic resistance is calculated according to the Colebrook-White formula;
4. hydraulic Panhandle efficiency coefficient of the gas pipeline is assumed to be equal to 0.968;
5. overall heat exchange coefficient with the soil containing the gas pipeline is assumed to be equal to 1.6 W/m^2/K.

Under these conditions, at a pressure and temperature at the gas pipeline inlet of 9.8 MPa and 30°C, respectively, and a daily capacity of 150 million m^3 (= 4404 tons of gas per hour), the following pressure and temperature values were obtained in the final section of the gas pipeline: 6.246 MPa and 10.4°C, which is very close to the set values.

To calculate the integral value of the entropy change according to formula (10), numerical integration by the trapezoidal rule was used, where their values obtained by solving a system of equations were taken as the velocity w and temperature T in the calculation nodes (1), (2), (10), (4), (5), and the number of calculated intervals was assumed to be 100. The integral value of the change in specific entropy for the imaginary reversible process of natural gas transportation at γ = 1 was 0.1328 kJ/kg/K.

The difference between the two values of entropy change obtained by the two methods described above is insignificant: 2.6%. This can be attributed to the error of both the used numerical integration method and entropy calculations based on thermal equations of state.

Note that when using values less than one for the coefficient γ, the difference in the values of specific entropy increases significantly. So, at γ = 0.9 it is equal to the specified difference is 30%, and at γ = 0.8 - 57%, which significantly exceeds the accuracy of calculations of absolute entropy values for the considered values of pressure p and temperature T. It is clear that the resulting differences in entropy changes cannot be attributed to the calculated errors.

7. The Limitations of the Described Procedure

It is revealed that the described procedure for verifying the validity of the above statement has limitations related to:

1. large errors in entropy values determined using complex correlation dependencies underlying the thermal equations of state;
2. the fact that the thermodynamic process pipeline transport of natural gas can be quite close to isentropic, and this leads to inaccuracies in determining the change in the entropy of the process obtained by subtracting the entropy large in absolute values.

The analysis of the entropy behavior in the considered case shows: within the framework of the one-dimensional gas flow model, the assumption that the work of the friction forces during the gas flow through the gas pipeline is entirely converted into thermal energy is justified with an accuracy acceptable for engineering applications.

Moreover, since this justification is based on the use of the integral definition of entropy (6) and the formulation of the second principle of thermodynamics in the form of equation (7), we conclude that the complete transition of the friction forces into internal thermal energy is a direct consequence of the second principle of thermodynamics in relation to the process of pipeline transport of natural gases.

8. The Natural Gas in a Supercritical State

It should be noted that in the initial sections of some modern main gas pipelines, the transported natural gas is in a supercritical state. In the supercritical state, natural gas has a high density, surface tension, solubility and other properties corresponding to a liquid, but it does not precipitate and completely fills the allocated volume, which is inherent in gas. It is known that in a supercritical state, natural gas has the properties of both a liquid and a gas, while not being in the full sense neither one nor the other [10].

Our studies [11-13] of the properties of natural gas in the state of supercritical fluid using Lee-Kesler-Plöcker EoS [14-16] show that with an increase in pressure at T=const, of all the macroscopic properties and thermodynamic potentials of natural gases in the supercritical region, the isobaric heat capacity of gas is the first to pass through its extremum, which is evidence of the beginning of a continuous transition of natural gas from a "gas-like", structureless state to a "liquid-like", condensed state. This transition reflects a noticeable increase in the forces of attraction between neighboring molecular structures and a decrease in the amount of thermal energy attributable to them in the overall energy balance of the hydrocarbon system.

It should be noted that in the initial sections of some modern main gas pipelines, the transported natural gas is in a supercritical state.

9. Conclusion

A verification of commonly used approval in pipeline hydraulics is carried out that the work of friction forces performed at the movement of real gas on the gas pipeline completely turns into thermal energy. By means of integral definition of entropy by Clausius it is shown that said thesis of conversion of friction forces operation into thermal energy of gas flow in finds its justification with acceptable accuracy for engineering applications in relation to 1-D setting of task of determination of longitudinal temperature field of gas. The limitations of the procedure used are defined. It is indicated that in the initial sections of some modern main gas pipelines, where operating pressure can exceed 15 MPa, the transported natural gas is in a supercritical state.

Notation

$p(x)$ - pressure, averaged over the cross section of the gas pipeline with the Eulerian coordinate x;

$\rho(x)$ - gas density, averaged over the cross section of the gas pipeline with the Eulerian coordinate x;

$w(x)$ - flow rate, averaged over the cross section of the gas pipeline with the Eulerian coordinate x;

$T(x)$ - temperature, averaged over the cross section of the gas pipeline with the Eulerian coordinate x;

T_{ext} - local temperature of environment;

h – specific enthalpy;

S – specific entropy;

D – internal pipe diameter;

λ – friction factor;

U – overall heat transfer coefficient;

β – local angle factor;

μ – J-T coefficient;

c_p – isobaric heat capacity;

dx - length of elementary cylindrical gas volume;

G - gas mass rate;

γ - artificial factor.

References

[1] Vasiliev O. F., Bondarev E. A., Voevodin A. F., Kanibolotskii A. M. Neizotermicheskoye techenie gaza w trubakh [Non-isothermal gas flow in pipes]. Nauka, Novosibirsk: 1978. 126 str.

[2] V. G. Fetisov et al. Mathematical modeling of non-stationary gas flow in gas pipeline. 2018 IOP Conf. Ser.: Mater. Sci. Eng. 327 022034.

[3] Schlichting H. Boundary layer theory. New York: 1979. 817 p.

[4] Cherny G. G. Gazovaya dinamika [Gas Dynamics]. Nauka, Moskva: 1988. 424 str.

[5] Kondepudi D., Prigogine I. Modern thermodynamics. From heat engines to dissipative structures. New York: 2014. 552 p.

[6] Vulis L. A. Termodinamika gazovykh potokov [Thermodynamics of gas flows]. Gosenergoizdat, Moskva: 1950. 304 str.

[7] Charnyj I. A. Osnovy gazovoi dinamiki [Fundamentals of gas dynamics]. Gostoptekhizdat, Moskva: 1961. 210 str.

[8] Strakhovich K. I. Gidro– i gazodinamika [Hydro and gas dynamics]. Nauka, Moskva: 1980. 313 str.

[9] Kochin N. E., Kibel I. A., Roze N. V. Teoreticheskaya gidrodinamika [Theoretical hydrodynamics]. Chast 2. Fizmatgiz, Moskva: 1963. 728 str.

[10] Arai Y., Sako T., Takebayashi Y. Eds. Supercritical Fluids – Molecular Interactions. Physical Properties, and New Applications. Springer-Verlag, Berlin, 2002. P. 445.

[11] Suleymanov V. A. Raschyet znachenii koeffitsienta Djoulya-Tomsona ispolzuya uravnenie sostoyaniya Li-Keslera-Plyekera dlya uslovii transporta prirodnogo gaza po magistralnym podvodnym gazoprovodam [Calculation of the Joule-Thomson coefficient value using the Lee-Kesler-Plocker EOS: a case of natural gas transportation through subsea gas mains]. Vesti gazovoy nauki. Moskva: Gazprom VNIIGAZ, 2020, no. 1 (42).

[12] Suleymanov V. A. Termicheskiye protsessy v truboprovodnom transporte prirodnogo gaza [Thermal processes in natural gas pipeline transport]. Vestnik Sankt Peterburgskogo Universiteta. Prikladnaya Matematika. Kompyuternaya Nauka. Kontrol Protsesov, 2020, tom 16, vyp. 3, str. 260–266.

[13] Suleymanov V. A. Raschyet izobarnoi i izokhornoi teployemkostei prirodnykh gazov v sverkhkriticheskom sostoyanii [Calculating isobaric and isochoric heat capacity of natural gases being in supercritical state]. Vesti gazovoy nauki. Moskva: Gazprom VNIIGAZ, 2021, no. 2 (47).

[14] Wales Stanley M. Phase Equilibria in Chemical Engineering. Butterworth Publishing. Boston, London, Sydney, Wellington, Durban, Toronto. 304 p.

[15] Lee B. I. A generalized thermodynamic correlation based on three-parameter corresponding states / B. I. Lee, M. G. Kesler // AIChE Journal. – 1975. – T. 21. – C. 510–527.

[16] Plöcker U. Calculation of high pressure vapor-liquid equilibria from a corresponding state correlation with emphasis on symmetric mixtures / U. Plöcker, H. Knapp, J. V. Prausnitz // Ind, Eng. Chem. Process Des. Dev. – 1978. – T. 17. – C. 324–332.