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Audit of Natural Gas Accounting Units in Order to Improve Measurement Accuracy

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Abstract. A technique of conducting audit of natural gas accounting systems based on pressure differential method is presented. Some sources of additional error of natural gas flow rate measurement are specified. In order to improve the accuracy of natural gas flow rate measurement specific measures are proposed: application of a pressure differential device optimal as to the accuracy of flow rate measurement; application of algorithm of differential pressure range switching in gas flow rate and volume calculators; installation of heat insulation on measuring section of the pipeline.

An acting system of natural gas accounting was taken as an example. All the necessary calculations were made to show the effectiveness of application of the proposed measures.

Keywords

Natural gas, accounting, flow rate, accuracy.

1. Introduction

In the light of price growth for energy carriers, including natural gas, application of energy saving technologies and saving of energy are top priorities. The problems of energy efficiency can only be solved provided there is an accurate accounting of energy carriers.

Natural gas is one of strategically important energy carriers. The accounting of natural gas in most cases is carried out by means of the pressure differential method. That is why improvement of measurement accuracy of these flow rate meters is of primary importance.

Because of the increased attention of gas-transporting and gas-distributing organizations to the accuracy of natural gas accounting the authors carried out audit of a number of acting natural gas accounting systems. The results of the audit show that a number of ways of measurement accuracy improvement are not applied at designing and maintaining accounting systems based on pressure differential flow rate meters. Application of these ways of accuracy improvement is not discordant to the requirements of the normative documents in force [1]-[3] and leads to the significant improvement of measurement accuracy in accounting systems based on the pressure differential method.

The goal of this work is to formulate the fundamentals of conducting audit of natural gas accounting systems based on the pressure differential method and to show the possibilities of accuracy improvement using a specific example.

2. The First Stage of the Audit

The audit is recommended to be done in two stages. The first stage is survey of the accounting system, examination of technical documentation for the system, comparison of the documentation data with actual technical characteristics of the system and of its components. Actual technical (metrological) characteristics of the components of the accounting system can be determined by means of metrological testing of the measuring devices using reference equipment. The error of the whole system, i.e. uncertainty of result of natural gas flow rate and quantity (volume) measurement, is determined on the basis of metrological characteristics of the components of the accounting system. At this stage some discrepancies can be found that require correction of technical documentation, replacement of some components or even

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reconstruction of the whole system. The recommendations developed during the first stage of the audit enable serious defects in the system to be eliminated and the system to be brought to conformance with the requirements of the normative documentation in force.

3. The Second Stage of the Audit

The second stage is analysis of the possibility to improve the accuracy of natural gas accounting in operating conditions of the accounting system which meets the requirements of the actual normative documents and technical documentation. The results of the second stage of audit show the efficiency of one or another way of accuracy improvement in operating conditions of the system and enable a decision to be taken on application of the proposed ways of accuracy improvement. In this work we concentrate our attention on the second stage of carrying out audit of natural gas accounting systems.

A. Optimal Pressure Differential Device

Application of an optimal pressure differential device (PDD) is an important step towards improvement of accuracy of natural gas flow rate measurement by means of the pressure differential method. According to the normative documents in force [1]-[3] the choice of relative area* (diameter of aperture) for PDD is not strictly regulated and thus there is some freedom of choice. When designing a natural gas accounting system there is a problem of choosing PDD optimal as to the accuracy of flow rate measurement. The fundamentals of calculating an optimal PDD are developed in [4], [5]. The calculation technique is given in [6] where there are formulae for calculation of relative area of PDD optimal as to the accuracy of flow rate measurement. In practice, however, a simplified technique is widely used. This simplified technique is also based on the ideas represented in [4]-[6] and consists in the following:

1) The initial value of differential pressure nominal limit Δp_{lim} is taken from the standard range of differential pressure limits (1.0; 1.6; 2.5; 4.0; 6.3 $\times 10^n$ Pa, n=0; 1; 2; 3…);
2) The values of PDD relative area m and relative error of flow rate measurement δ_q are calculated for the given parameters of natural gas flow, measuring section of pipeline, metrological characteristics of measuring devices, given maximum flow rate of gas and taken differential pressure nominal limit Δp_{lim};
3) The next differential pressure nominal limit Δp_{lim} is taken from the standard range;
4) Steps 2 and 3 are repeated until the minimum of flow rate measurement error δ_q dependence on PDD relative area m is found;
5) The relative area of PDD at which relative error of flow rate measurement is minimal is taken as optimal relative area of PDD for the given system.

The simplified technique of optimal PDD calculation is depicted on Fig. 1.

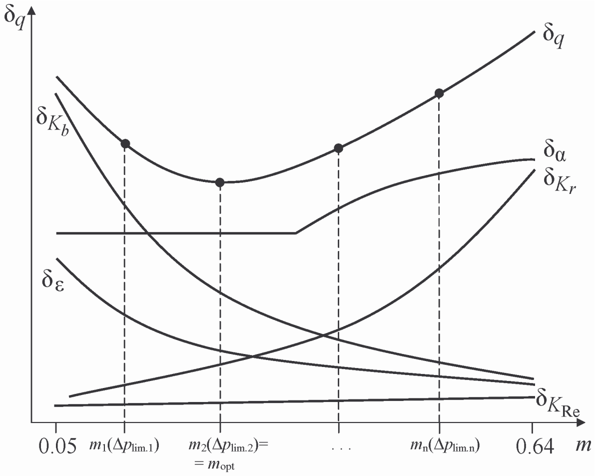

Fig. 1. Dependence of component errors of flow rate measurement on relative area of pressure differential device m: δ_q is relative error of flow rate measurement; δ_α is relative error of flow rate coefficient; δ_ε is relative error of expansibility factor; δ_{K_r} is relative error of pipeline internal surface roughness correction coefficient; δ_{K_b} is relative error of orifice plate edge blunting correction coefficient (applicable only for orifice plates); $\delta_{K_{\text{Re}}}$ is relative error of Reynolds number correction coefficient.

The existence of the minimum on the curve of flow rate measurement error δ_q dependence on PDD relative area m is explained by the behaviour of component error curves (see Fig. 1).

An orifice plate is the most widespread PDD in pressure differential gas accounting systems. Let's consider an example of optimal orifice plate calculation for an acting system of natural gas accounting with technical specifications given in Table I. Results of optimal orifice plate calculation according to the simplified technique are given in Table II.

We can see from the results obtained (see Table II) that relative error of flow rate measurement is minimal ($\delta_{q.\text{min}}$=0.814 %) for orifice plate with m_{opt}=0.38 ($d_{20.\text{opt}}$=247.43 mm). The differential pressure nominal limit for this orifice plate is 63 kPa. Application of an orifice plate with another aperture diameter and differential pressure nominal limit, e.g. neighbouring 40 kPa, in the same accounting system would lead to increase in relative error of flow rate measurement by 0.234 % (δ_q=1.048 %). So we can see that one of the ways to minimize the error of flow rate measurement is application of an optimal orifice plate calculated according to the above-mentioned technique.

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* Relative area of PDD is square ratio of PDD aperture diameter to pipeline internal diameter.

TABLE I

BASIC TECHNICAL SPECIFICATIONS OF NATURAL GAS ACCOUNTING SYSTEM

No.	Parameter name	Parameter value
1	Type of pressure differential device	Orifice plate
2	Aperture diameter at 20 ºC temperature d_{20} (mm)	247.43
	Medium parameters	
3	Type of medium	Dry natural gas
4	Gas density at standard conditions** ρ_s (kg/m^3)	0.699
5	Content of nitrogen in gas x_{N2} (%)	0.85
6	Content of carbon dioxide in gas x_{CO2} (%)	0.25
7	Gas absolute pressure p (MPa)	4.4
8	Registered value of gas temperature in winter T_{RT} (ºC)	+5
9	Registered value of gas temperature in summer T_{RT} (ºC)	+10
10	Maximum flow rate of gas reduced to standard conditions $q_{s.\max}$ (m^3/h)	340116.78
11	Average flow rate of gas reduced to standard conditions $q_{s.\mathrm{av}}$ (m^3/h)	204070.07
12	Minimum flow rate of gas reduced to standard conditions $q_{s.\min}$ (m^3/h)	44215.18
13	Differential pressure at maximum flow rate $\Delta p_{\max}$ (kPa)	63
14	Differential pressure at average flow rate Δp_{av} (kPa)	22.55
15	Differential pressure at minimum flow rate $\Delta p_{\min}$ (kPa)	1.06
	Pipeline parameters	
16	Internal pipeline diameter at 20 ºC temperature D_{20} (mm)	401.85
17	External pipeline diameter at 20 ºC temperature $D_{20.\mathrm{ex}}$ (mm)	433.85
18	Absolute roughness of pipeline wall internal surface R_a (mm)	0.20
	Measuring equipment parameters	
19	Type of differential pressure gauge	ROSEMOUNT 3051
20	Upper limit of differential pressure measurement (kPa)	63
21	Differential pressure gauge grade of accuracy $S_{\Delta p}$ (%)	0.15
22	Type of absolute pressure gauge	ROSEMOUNT 3051 CA
23	Upper limit of pressure measurement (MPa)	7
24	Absolute pressure gauge grade of accuracy S_p (%)	0.15
25	Type of thermometer	PPS.2-T
26	Lower limit of temperature measurement (ºC)	-20.0
27	Upper limit of temperature measurement (ºC)	80.0
28	Thermometer grade of accuracy S_T (%)	0.50
29	External diameter of the thermometer case $d_{T.ex}$ (mm)	20
30	Internal diameter of the thermometer case $d_{T.in}$ (mm)	8
31	Placing of the thermometer	Downstream of orifice plate
32	Distance between orifice plate and the thermometer L_T (m)	5.8
33	Depth of the thermometer immersion into the pipeline L_{TI} (mm)	123.7
	External air parameters	
34	Temperature of external air in winter T_{air} (ºC)	-15
35	Wind speed in winter v_{air} (m/sec)	5
36	Temperature of external air in summer T_{air} (ºC)	+20
37	Wind speed in summer v_{air} (m/sec)	5

** Standard conditions are 20 ºC temperature and 101325 Pa pressure.

TABLE II

RESULTS OF OPTIMAL ORIFICE PLATE CALCULATION

Differential pressure nominal limit Δp_{lim} (kPa)	40	63	100	160
PDD aperture diameter at 20 ºC temperature d_{20} (mm)	271.90	247.43	223.73	201.26
PDD relative area m	0.46	0.38	0.31	0.25
Pressure losses on orifice plate $\Delta\overline{\varpi}$ (kPa)	21.09	38.04	67.12	116.79
Relative error of flow rate measurement δ_q (%)	1.048	0.814	0.868	1.013

B. Differential Pressure Range Switching

The next step towards improvement of accuracy of gas flow rate measurement by means of the pressure differential method is application of an algorithm of differential pressure range switching in calculators of gas flow rate and volume. This algorithm can be applied in gas accounting systems based on flow rate calculators and modern high-quality differential pressure gauges. When applying this algorithm the range of flow rate measurement can be extended to $q_{\max}/q_{\min}$=10/1 with the relative error of flow rate measurement of 1…2 % in the specified range. The methodological bases of this algorithm are given in [7]. The advantage of this way of flow rate range widening in comparison to other methods is that the specified metrological characteristics can be secured in natural gas accounting system based on one differential pressure gauge [7].

For the accounting system with technical specifications given in Table 1 results of application of differential pressure range switching algorithm are given in Table III and shown on Fig. 2 and Fig. 3.

TABLE III
RESULTS OF CALCULATION OF DIFFERENTIAL PRESSURE AND FLOW RATE MEASUREMENT ERRORS WITH APPLICATION OF DIFFERENTIAL PRESSURE RANGE SWITCHING ALGORITHM

Flow rate q_s (%)	Differential pressure Δp (kPa)	Relative error of differential pressure measurement $\delta_{\Delta p}$ (%)	Relative error of flow rate measurement δ_q (%)
100	63.00	0.1501	0.8126
70	30.73	0.3076	0.8196
50	15.64	0.1813	0.8092
40	10.00	0.2835	0.8164
30	5.62	0.1626	0.8080
20	2.49	0.3663	0.8244
10	0.63	1.1469	0.9874

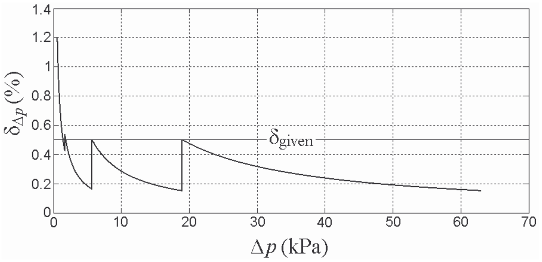

Fig. 2. Relative error of differential pressure measurement $\delta_{\Delta p}$ versus differential pressure Δp with application of differential pressure range switching algorithm.

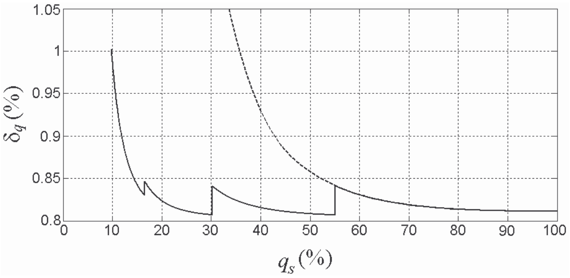

Fig. 3. Relative error of flow rate measurement δ_q versus flow rate q_s with application of differential pressure range switching algorithm (——) and without the algorithm (-----).

In this example the differential pressure gauge is calibrated in the range from zero to upper right limit (Δp_{URL}=63 kPa) [8]. Division of the differential pressure range into subranges is done in such way that relative error of differential pressure measurement $\delta_{\Delta p}$ does not exceed given value of this error δ_{given}=0.5 % (see Fig. 2). In this example the differential pressure range is divided into four subranges. The limits of each subrange are calculated according to formulae given in [7]. Variation of relative error of flow rate measurement with respect to flow rate is shown on Fig. 3. We can see from Fig. 3 that the range with relative error of flow rate measurement δ_q less than 1 % was widened from 36…100 % q_s to 10…100 % q_s with application of the differential pressure range switching algorithm.

C. Heat Insulation

A negative factor during natural gas accounting is appearance of additional errors of temperature measurement due to temperature difference between the gas flow and the external air on the measuring section of the pipeline. The temperature regime of gas flow is developed on the basis of the work accomplished on gas (compression, heating, pressure reduction) as well as on the basis of design characteristics of the pipeline and conditions of pipeline ditching. That is why there is a variable temperature regime of gas flow on the sections of gas pipelines downstream of pressure reduction units, compressor units, gas heating units, at the exit of the pipeline from underground above the surface, etc. In pressure differential gas accounting systems installed on these sections of pipelines an additional error of flow rate measurement appears due to additional error of temperature measurement ΔT. This additional error of temperature measurement includes the following component errors:

- an error caused by heat exchange between the thermometer case and the pipeline wall (ΔT_T);
- an error caused by heat exchange between the pipeline wall and the external air (ΔT_x);
- an error caused by temperature decrease as the gas is throttled through pressure differential device (ΔT_{thr}).

1) *Error caused by heat exchange between the thermometer case and the pipeline wall* ΔT_T.

Because temperature of the immersed end of the thermometer case differs from the pipeline wall temperature, heat exchange between them takes place through heat conduction and heat radiation (see Fig. 4). At gas temperatures typical for gas transportation and gas distribution processes, heat exchange by heat conduction is of a higher intensity than heat exchange by heat radiation. The value of ΔT_T error depends significantly on temperature difference between the gas and the external air, the flow rate and pressure of the gas, the thickness of the thermometer case wall and the depth of the thermometer immersion into the pipeline.

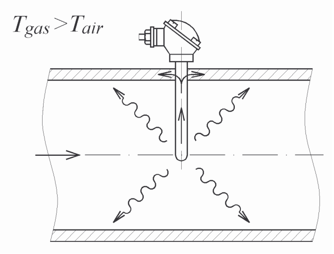

Fig. 4. Heat exchange between thermometer case and pipeline wall.

On the basis of previous theoretical analysis we propose the value of the additional error of temperature measurement ΔT_T to be calculated with application of the formulae given in [9] as follows:

$$\Delta T_T = \Delta T_{TC} + \Delta T_{TR}\,; \qquad (1)$$

$$\Delta T_{TC} = -\frac{T_{RT} - T_{w.in}}{\mathrm{ch}(b \cdot L_{TI})} \cdot \frac{\mathrm{sh}(b \cdot L_{TS})}{b \cdot L_{TS}}\,; \qquad (2)$$

$$\Delta T_{TR} = -\frac{c_0 \cdot \varepsilon_T}{\alpha_T} \cdot \left(\left(\frac{T_{RT}}{100} \right)^4 - \left(\frac{T_{w.in}}{100} \right)^4 \right), \qquad (3)$$

where ΔT_{TC} is error caused by heat exchange between the thermometer case and the pipeline wall by heat conduction; ΔT_{TR} is error caused by heat exchange between the thermometer case and the pipeline wall by heat radiation; T_{RT} is temperature registered by the thermometer; $T_{w.in}$ is temperature of pipeline wall internal surface (can be calculated according to [10]); L_{TI} is depth of the thermometer immersion into the pipeline; L_{TS} is length of the thermometer sensing element; b is coefficient that depends on design characteristics of the thermometer and heat transfer coefficient from gas flow to the thermometer case; c_0=5.67 Wt/(m^2·K^4) is blackbody heat radiation coefficient; ε_T is the thermometer case rate of blackness; α_T is convective heat transfer coefficient from gas flow to the thermometer case (can be calculated according to [10]).

For the gas accounting system with technical specifications given in Table I the calculated values of the ΔT_T error according to (1) are as follows: ΔT_T =-0.0453 ºC in winter and ΔT_T =+0.2427 ºC in summer (see Table IV). The values of the ΔT_T error are small for the accounting system under consideration due to a large pipeline internal diameter and a long immersed part of the thermometer. And in a gas accounting system with D_{20}=100 mm, for example, the ΔT_T error can be as high as -1.5 ºC in winter and +3 ºC in summer.

The ΔT_T error can be reduced significantly or even eliminated by using a heat insulating gasket between the thermometer case and the pipeline wall and by heat insulation of measuring section of the pipeline which will lead to reduction of temperature difference between the thermometer case and the pipeline wall.

2) *Error caused by heat exchange between the pipeline wall and the external air ΔT_x.*

One of the input values in the basic equation of gas flow rate calculation [1]-[3] developed on the basis of laws of mass and energy conservation [11] is gas temperature intermediately upstream of PDD (in *1-1* cross-section, see Fig. 6). The thermometer can not be installed intermediately upstream of PDD because this will distort readings of the differential pressure gauge. Thus the thermometer is installed at a distance from the PDD. According to the requirements of the new GOST interstate standards [2], [3] the distance between PDD and thermometer with $0.03 \cdot D_{20} < d_{T.ex} \leq 0.13 \cdot D_{20}$ which does not introduce additional uncertainty to the discharge coefficient equals $20 \cdot D_{20} \ldots 30 \cdot D_{20}$ in case of mounting the thermometer upstream of PDD and $5 \cdot D_{20} \ldots 15 \cdot D_{20}$ in case of mounting the thermometer downstream of PDD. Due to heat exchange between gas flow and external air the gas temperature varies along the pipeline (it approaches the external air temperature, see Fig. 5). That is why the gas temperature intermediately upstream of PDD is different from that in the place of thermometer mounting. This temperature difference is an error caused by heat exchange between the pipeline wall and the external air ΔT_x. The value of ΔT_x error, besides gas and air temperatures, gas pressure and flow rate, depends significantly on place of thermometer mounting (distance between thermometer and PDD).

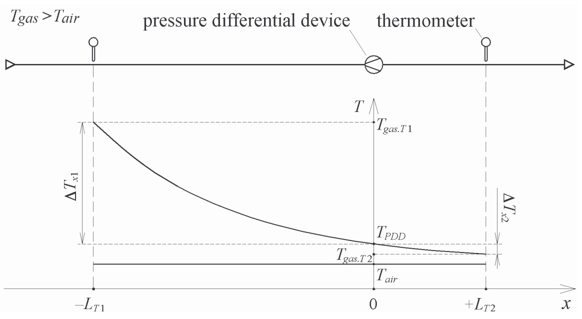

Fig. 5. Gas temperature variation on the measuring section of the pipeline:
$T_{gas.T}$ is gas temperature in the place of thermometer mounting; T_{PDD} is gas temperature at pressure differential device; T_{air} is temperature of the external air; L_T is distance between thermometer and pressure differential device.

The value of the additional error of temperature measurement ΔT_x is proposed to be calculated according to the formula derived on the basis of [12] as follows:

$$\Delta T_x = (T_{gas.T} - T_{air}) \cdot \left(1 - \mathrm{e}^{\frac{K \cdot L_T}{q_{m.gas} \cdot c_{p.gas}}} \right), \qquad (4)$$

where $T_{gas.T}$ is natural gas temperature in the place of thermometer mounting; T_{air} is temperature of the external air; K is coefficient of heat transfer from gas flow to external air (can be calculated according to [10]); L_T is distance between thermometer and PDD; $q_{m.gas}$ is mass flow rate of natural gas; $c_{p.gas}$ is specific heat capacity of natural gas.

For the gas accounting system with technical specifications given in Table I the following values of the ΔT_x error were obtained on the basis of calculations according to (4): ΔT_x =-0.1102 ºC in winter and ΔT_x =+0.2257 ºC in summer (see Table IV). In some cases at considerable distances between the thermometer and PDD, considerable difference between gas and external air temperatures and at small flow rates of gas the absolute value of ΔT_x error can reach 3 ºC.

The ΔT_x error can be eliminated by installation of heat insulation on measuring section of the pipeline. This

TABLE IV

RESULTS OF ADDITIONAL-ERROR CALCULATION

Parameter name	Parameter value	
	For average flow rate in winter	For minimum flow rate in summer
True value of gas temperature at pressure differential device T_{PDD} (ºC)	+5.2492	+9.5361
Additional error of temperature measurement caused by heat exchange between the thermometer case and the pipeline wall ΔT_T (ºC)	-0.0453	+0.2427
Additional error of temperature measurement caused by heat exchange between the pipeline wall and the external air ΔT_x (ºC)	-0.1102	+0.2257
Additional error of temperature measurement caused by temperature decrease as the gas is throttled through pressure differential device ΔT_{thr} (ºC)	-0.0937	-0.0045
Combined additional error of temperature measurement ΔT (ºC)	-0.2492	+0.4639
Additional relative error of flow rate measurement due to the combined additional error of temperature measurement δ_q (%)	+0.0621	-0.1115
Additional absolute error of flow rate measurement due to the combined additional error of temperature measurement Δ_q (m^3/h)	+111.7158	-44.5904

will reduce heat flow from natural gas to external air and consequently reduce gas temperature variation along the pipeline.

3) *Error caused by temperature decrease as the gas is throttled through pressure differential device* ΔT_{thr}.

This error appears in case of mounting thermometer downstream of PDD. Gas temperature variation between PDD and thermometer is caused by the following two processes:

- decrease of gas temperature due to convergence of gas stream during gas discharge through PDD (see Fig. 6, part of temperature curve between *1-1* and *2-2* cross-sections);
- partial restoration of gas temperature due to divergence of gas stream (see Fig. 6, part of temperature curve between *2-2* and *3-3* cross-sections).

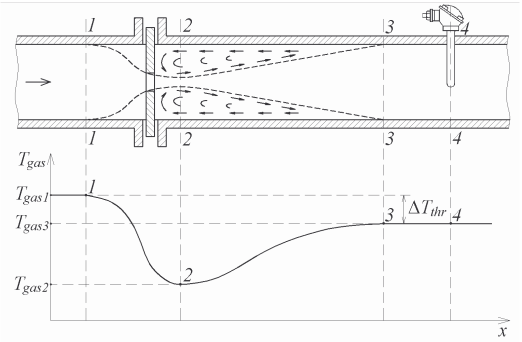

Fig. 6. Gas temperature variation during gas discharge through pressure differential device.

Gas state between *1-1* and *2-2* cross-sections can be described roughly by the equation of isentropic process [13]. Restoration of gas stream structure takes place along the distance between *2-2* and *3-3* cross-sections. Gas pressure and temperature restoration between *2-2* and *3-3* cross-sections is partial and not complete because of the pressure losses on PDD. A lot of scientists assume that the distance between *2-2* and *3-3* cross-sections is shorter than the distance between thermometer and PDD. However, for natural gas accounting systems operating at large ratio of differential pressure to absolute pressure (medium pressure systems) this assumption may be wrong.

Provided that the restoration of gas stream structure is completed prior to the place of thermometer mounting the ΔT_{thr} error can be calculated according to the equation of throttle effect (Joule-Thomson effect) [13]. Taking into account the fact that pressure difference between *1-1* and *3-3* cross-sections is equal to pressure losses on PDD the ΔT_{thr} error can be calculated by the following integral equation of throttle effect:

$$\Delta T_{thr} = -\int_{p-\Delta\overline{\omega}}^{p} D_h \, dp \,, \tag{5}$$

where p is natural gas pressure; $\Delta\overline{\omega}$ is pressure loses on PDD; D_h is Joule-Thomson coefficient (can be calculated according to [14]).

For the gas accounting system with technical specifications given in Table I the calculated values of the ΔT_{thr} error according to (5) are as follows: ΔT_{thr} =-0.0937 ºC in winter and ΔT_{thr} =-0.0045 ºC in summer (see Table IV). The ΔT_{thr} error is always negative because pressure losses on PDD lead to temperature decrease. In some cases at high flow rates (and high pressure losses on PDD) the ΔT_{thr} error can reach -0.5 ºC.

The ΔT_{thr} error can be avoided by placing the thermometer upstream of PDD.

The combined additional error of temperature measurement caused by the above-mentioned factors can be calculated as follows:

$$\Delta T = \Delta T_T + \Delta T_x + \Delta T_{thr}. \tag{6}$$

The additional relative error of natural gas flow rate measurement due to the combined additional error of temperature measurement can be calculated as follows:

$$\delta_q = \left(\frac{q_s(T_{RT})}{q_s(T_{PDD})} - 1 \right) \cdot 100\,\%, \tag{7}$$

where $q_s(T_{RT})$ is natural gas flow rate reduced to standard conditions calculated with registered value of gas temperature T_{RT}; $q_s(T_{PDD})$ is natural gas flow rate reduced to standard conditions calculated with true value of gas temperature at PDD T_{PDD}.

The true value of gas temperature at PDD can be calculated as follows:

$$T_{PDD} = T_{RT} - \Delta T\,. \tag{8}$$

Results of additional-error calculation for the gas accounting system with technical specifications given in Table I are represented in Table IV.

As we can see from calculation results in Table IV the accounting system with technical specifications given in Table I overestimates the results of natural gas volume measurement by 111.72 m^3 every hour in winter and underestimates the results of natural gas volume measurement by 44.59 m^3 every hour in summer due to the additional errors of temperature measurement. Implementation of the proposed measures to eliminate the additional errors of temperature measurement will make it possible to avoid distortion of the measurement results and will improve the accuracy of this gas accounting system.

4. Conclusion

On the basis of the results of theoretical analysis and audit of acting natural gas accounting systems based on the pressure differential method the following measures are proposed to improve the accuracy of natural gas flow rate and volume measurement:

- Application of the technique to calculate a pressure differential device optimal as to the accuracy of flow rate measurement. This will secure minimal error of flow rate measurement in the conditions of a specific gas accounting system with the available measuring equipment.
- Application of algorithm of differential pressure range switching in gas flow rate and volume calculators to widen the range of flow rate measurement to $q_{\max}/q_{\min}$=10/1 with the relative error of flow rate measurement of 1…2 % in the specified range.
- Installation of heat insulation on the measuring section of the pipeline to eliminate additional error of flow rate measurement caused by additional errors of temperature measurement.

The effectiveness of application of the proposed measures is proved by the calculations for an acting gas accounting system.

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