TRENDS OF DENSITY MEASUREMENT BY INTERNATIONAL TRANSPORT OF NATURAL GAS – DIRECT OR INDIRECT MEASUREMENT?

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Abstract – Czech Republic has a tradition in the international transport of Russian type natural gas into the states of West Europe. The accurate measurement of the transferred amount belongs to the long term priorities of both the operator and the state, which ensures correctness and uniformity of the measurement in this legally regulated sphere of metrology.

Keywords: density, pTZ method, vibrating densitometer.

1. INTRODUCTION

When measuring the flowrate of natural gas by pressure difference elements (orifices, nozzles and Venturi tubes), natural gas density is one of the most important parameters. In practice, the density of flowing natural gas is determined by means of two basic methods. One is applied for measuring the density using vibrating densitometers and the second is for determining the natural gas density using the pTZ method.

2. DIRECT DENSITY MEASUREMENT

In the gas industry, the instruments that are most often used for direct measurement of the density of natural gas are vibrating densitometers. They use the dependence of changes in the resonant frequency of a vibrating cylinder on circumfluent gas density. The gas density sensor consists of a thin metal cylinder which vibrates on its eigenfrequency. The gas passes along its inside and outside surface and is in contact with the vibrating surface of the cylinder. The mass of the gas which vibrates with the cylinder is dependent on gas density. If the mass of the gas increases, the eigenfrequency decreases. The gas density can be derived from the frequency of the vibrations.

The dependence of the gas density on the transducer time period τ is parabolic:

$$\rho = C_0 + C_1\tau + C_2\tau^2, \tag{4}$$

where C_0, C_1 and C_2 are calibration constants of the relevant instrument.

The possible range of these densitometers is for example $(1 \div 400)$ kg·m^{-3}. The accuracy of the vibrating densitometers used for the measurement of the density of natural gas is approximately 0.15 % of the measured value. The temperature range can be for example $(-20 \div 80)$ °C. The temperature coefficient is approximately 0.001 kg·m^{-3}·°C^{-1}.

One advantage of vibrating densitometers is in the direct measurement of the gas density. A typical installation of a vibrating densitometer to a pipe is shown in Fig. 1. The vibrating densitometer is installed behind a primary device which measures the gas flow (orifice, nozzle, Venturi tube). A disadvantage of vibrating densitometers is that measured gas must be brought into the densitometer through a pipe. This disadvantage takes effect, when the temperature of the ambient is very different to that of the flowing gas. In this case, the gas temperature in the pipe changes and the gas density does too. This effect is partially compensated by a temperature reservoir in which the vibrating densitometer is installed.

There are more possibilities of installation of vibrating densitometers in [5]. In the case of flow measuring by orifice plate, there are two methods.

First is pressure-recovery method, so-called since it utilizes the recovery of pressure drop downstream of the orifice plate to drive the sample through the densitometer. The sample is returned at the downstream tapping point, but diametrically opposite to the tapping points used for differential pressure. Care shall be taken to ensure that there is a sufficient pressure drop to set up a flow in the sample line. With this method, a probe is used at the sampling point. This method is used in our case (Fig. 1).
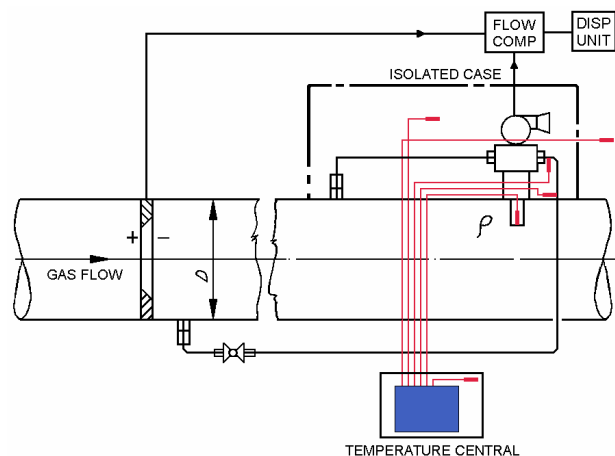

Fig. 1: Typical installation of vibrating densitometer to the pipe.

Installation of any restriction in the sample line, such as filters, flow control valves etc, should be between the sampling point and the densitometer. The density at the upstream (preferred) or downstream tapping point shall be used in flow calculations in accordance with ISO 5167-1. To further reduce temperature differences, filters upstream of the densitometers may be installed in pockets into the line. Due to the pressure drop created, flow control valves shall not be upstream of the densitometer as this can change the process conditions of the gas being measured by the density cell.

The second installation method of vibrating densitometer is method with sample gas to vent. This method is shown in Fig. 2. In this case, special care shall be taken to prevent pipewall resident matter from entering the densitometer sampling system and meter, e.g. by applying an appropriate filter.
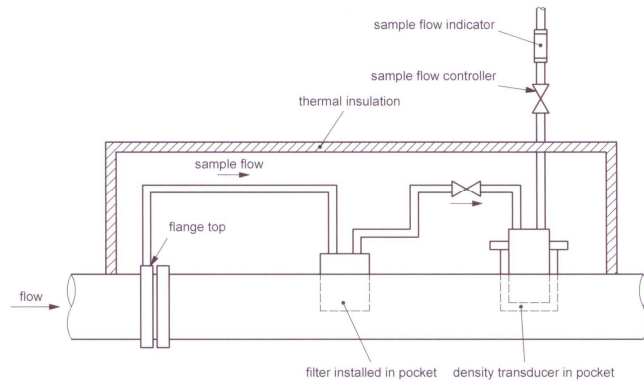

Fig. 2: Installation of vibrating densitometer with sample gas to vent.

Care shall be taken to avoid low temperature caused by a pressure drop over the flow controller, which can result in icing, condensation and blocking of sample outlet. Care shall also be taken to avoid differences in pressure between the pipe and the density transducer.

If it is not possible to obtain temperature equilibrium, a correction for the temperature difference between the densitometer and pipe may be calculated using equation:

$$\rho_L = \rho_c \frac{T_d}{T_L} \frac{p_L}{p_d} \frac{Z_d}{Z_L}, \qquad (5)$$

where T_d is the temperature in density transducer, T_L is the temperature in pipe, p_d is pressure in the densitometer, p_L is the pressure at the required location in the pipe, Z_d is the compression factor in the densitometer and Z_L is the compression factor in the pipe at the required location. Z_d and Z_L must be calculated from the available knowledge of the gas composition in the pipe.

This disadvantage is eliminated if the pTZ method is used. The values of the density of the flowing gas are calculated from the values of the pressure and temperature taken directly at the point of the installation of the primary device. However, the other gas parameters must also be known, and in the process of determining these values uncertainties occur.

3. INDIRECT DENSITY MEASUREMENT

In the case that the pTZ method is used for determining the natural gas density, it is necessary to know not only the temperature and pressure, but also its compression factor. There are several calculation methods that can be used to determine this. Among the most widely used methods are AGA NX-19-mod [1], AGA8-92DC [2] and SGERG-88 [3]. In order to be able to use these methods, it is necessary to know not only the temperature and pressure of the relevant natural gas, but also its chemical composition, relative density and the superior calorific value.

The AGA NX-19-mod method is described in Guideline VDI/VDE 2040 Part 2 [1]. In order to use this method, it is necessary to know the temperature and pressure of the natural gas, the carbon dioxide (CO_2) and the nitrogen (N_2) mole fractions and its relative density.

The AGA8-92DC method is described in the ISO 12213-2 Standard [2]. In order to use this method, it is necessary to know the temperature and pressure of the natural gas and its exact chemical composition.

The SGERG-88 method is described in the ISO 12213-3 Standard [3]. In order to use this method, it is necessary to know the temperature and pressure of the natural gas, the carbon dioxide (CO_2), the nitrogen (N_2) or the hydrogen (H_2) mole fractions. The other parameters that need to be known are relative density and the superior calorific value H_S.

The choice of method for determining compression factor is given by the range of the applicability of the methods and also by the available information about the given natural gas.

The uncertainty of each of the methods used for determining the compression factor of natural gas differs. For example, the following equation is used to calculate the compression factor using the SGERG-88 method [4]:

$$\delta_Z(\%) = \left([A_{Hs}\delta_{Hs}(\%)]^2 + [A_d\delta_d(\%)]^2 + \right.$$
$$\left. + [A_{CO2}\delta_{CO2}(\%)]^2 + [A_T\delta_T(\%)]^2 + [A_p\delta_p(\%)]^2 \right)^{1/2}, \qquad (6)$$

where the sensitivity coefficients A_{Hs}, A_{GR}, A_{CO2}, A_T, A_p and the errors of the devices measuring the input values δ_{Hs}, δ_{GR}, δ_{CO2}, δ_T, δ_p are given in Table 1. In the case of non-correlated input quantities, the final uncertainty of this method is 0.11 %. In the case of correlated input quantities of the superior calorific value and mole fraction of CO_2, the final uncertainty is 0.16 %.

Table 1: Sensitivity coefficients and errors of measuring devices for the SGERG-88 method.

Gas input parameter		Sensitivity coefficient	Device error
Quantity	Unit	[-]	[%]
Superior calorific value	[MJ.m^{-3}]	0.28	0.15
Relative molar mass	[-]	0.22	0.20
CO_2 mole fraction	[mol]	0.33	0.20
Temperature	[K]	0.70	0.05
Pressure	[MPa]	0.15	0.30

The uncertainty of the density can be expressed using the pTZ method, where it is necessary to determine the sensitivity coefficients. Gas density determined by the pTZ method is given by the relation:

$$\rho_1 = \rho_{std} \frac{Z_{std}}{Z_1} \frac{p_1}{p_{std}} \frac{T_{std}}{T_1} . \qquad (7)$$

The relations hold for the sensitivity coefficients:

$$A_{\rho_{std}} = \frac{\partial \rho_1}{\partial \rho_{std}} = \frac{Z_{std}}{Z_1} \frac{p_1}{p_{std}} \frac{T_{std}}{T_1} , \qquad (8)$$

$$A_{Z_1} = \frac{\partial \rho_1}{\partial Z_1} = -\rho_{std} \frac{Z_{std}}{Z_1^2} \frac{p_1}{p_{std}} \frac{T_{std}}{T_1} , \qquad (9)$$

$$A_{Z_{std}} = \frac{\partial \rho_1}{\partial Z_{std}} = \rho_{std} \frac{1}{Z_1} \frac{p_1}{p_{std}} \frac{T_{std}}{T_1} , \qquad (10)$$

$$A_{p_1} = \frac{\partial \rho_1}{\partial p_1} = \rho_{std} \frac{Z_{std}}{Z_1} \frac{1}{p_{std}} \frac{T_{std}}{T_1} , \qquad (11)$$

$$A_{p_{std}} = \frac{\partial \rho_1}{\partial p_{std}} = -\rho_{std} \frac{Z_{std}}{Z_1} \frac{p_1}{p_{std}^2} \frac{T_{std}}{T_1} , \qquad (12)$$

$$A_{T_1} = \frac{\partial \rho_1}{\partial T_1} = -\rho_{std} \frac{Z_{std}}{Z_1} \frac{p_1}{p_{std}} \frac{T_{std}}{T_1^2} , \qquad (13)$$

$$A_{T_{std}} = \frac{\partial \rho_1}{\partial T_{std}} = \rho_{std} \frac{Z_{std}}{Z_1} \frac{p_1}{p_{std}} \frac{1}{T_1} . \qquad (14)$$

The final uncertainty of the gas density calculated using the pTZ method is:

$$u_{\rho_1} = \left(\left(A_{\rho_{std}} u_{\rho_{std}} \right)^2 + \left(A_{Z_1} u_{Z_1} \right)^2 + \left(A_{Z_{std}} u_{Z_{std}} \right)^2 + \right.$$
$$\left. + \left(A_{p_1} u_{p_1} \right)^2 + \left(A_{p_{std}} u_{p_{std}} \right)^2 + \left(A_{T_1} u_{T_1} \right)^2 + \left(A_{T_{std}} u_{T_{std}} \right)^2 \right)^{1/2} . \qquad (15)$$

4. EXPERIMENTAL MEASUREMENT

The first method is utilised as the primary one, providing data for the calculation of natural gas flow. The second method serves for the continuous check of the results of the first one. Traditionally, the direct gas density measurement was preferred as the primary method of gas density determination for the purpose of gas transit through Czech Republic.

But due to the development of the new technologies and the measurement technique the praxis in this area began to change in the last years. In the cases, when the top quality sensors of the working quantities (temperature, pressure, gas composition, ...) are installed in the flow measurement system, the new trends emerge in this field – not to use the direct density measurement method as the primary one, because it is relatively technically and financially demanding. Because of these trends, the Czech Metrology Institute tried to execute a study based on the long term experimental measurements. The target was to determine the technical possibilities and limiting parameters of the direct natural gas density measurement comparing to the pTZ method in the whole year working conditions of natural gas transport.

A control station with the possibility of data storage was used for experimental measurement of temperature. The measurement control station was located at an international natural gas delivery station. It was installed at the pipeline as close as possible to the density measurement instrument. With the aid of the control station, the temperature was read at the points of the pressure tappings, at the input of the vibrating densitometer, inside the actual vibrating densitometer and before the primary device. Furthermore, the temperature inside the case with the vibrating densitometer and the ambient temperature were measured (Fig. 1). The density of the natural gas was also measured by the vibrating densitometer.

Based on long-term experience with measurement of the flow and density of natural gas, it was proposed to minimize the differences in the values of the density determined by the pTZ method (SGERG-88) and the method of direct measurement. In extreme cases, these variations reached 0.3 kg·m⁻³.

Fig. 3 shows the curves of the natural gas density which was measured directly by the vibrating densitometer and calculated using the pTZ method. These values were measured inside the pipe without any additional insulation. The graph also shows the temperature of the ambient. The data was recorded by the control station for a period of 24 hours at five-minute intervals.
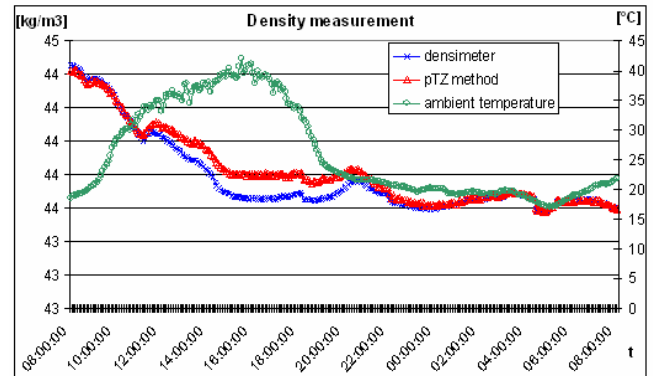

Fig. 3: Density measurement with basic insulation.

As is obvious from the graph, during the measurement of the density of the natural gas using the vibrating densitometer, the natural gas inside the pipe is heated as a result of increasing temperature of the ambient. Through this pipe, natural gas is led into the vibrating densitometer, thus introducing a systematic error, which can be minimized with the application of additional insulation.

Fig. 4 shows the data measured inside the pipe with the additional insulation. In this case, the differences in the values of the density determined by the pTZ method and the method of direct measurement are smaller.
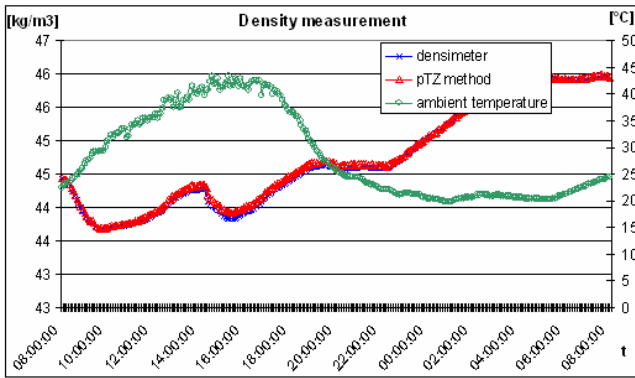
Fig. 4: Density measurement with I level insulation.

In order to minimize the differences between the gas density using the pTZ method and the direct measurement method using the vibrating densitometer, several methods of pipe insulation were proposed. In practice the so-called "three-insulations" method proved best. Here, not only the measuring pipe is insulated but also the pipe leading to the vibrating densitometer and the case containing the actual vibrating densitometer too. Fig. 5 shows the data measured inside the pipe with this type of insulation.
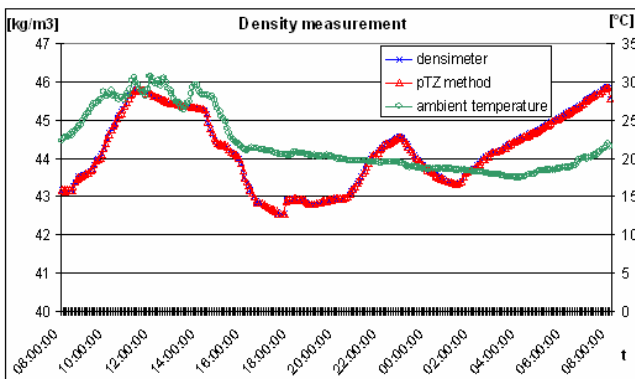

Fig. 5: Density measurement with II level insulation.

Fig. 6 shows the ambient temperature effect on differences of the density measured by the vibrating densitometer and the density determined by the pTZ method for all presented methods of insulation.
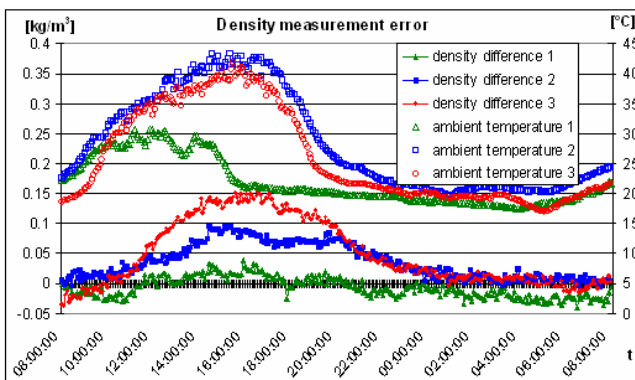

Fig. 6: Ambient temperature effect on vibrating densitometer measurement of gas density.

As is obvious from the graph, the additional insulation influenced the accuracy of density measurement by the vibrating densitometer. After the sufficient insulation, the values measured by the vibrating densitometer are nearly equal to values determined by the pTZ method. This effect is shown on table 2.

Installation of the vibrating densitometer with additional insulation is shown in Fig. 7. This figure shows level II insulation of measuring system.

Fig. 7: Level II of insulation.

The gas pressure during the experimental measurement was approx. 60 bar. The gas temperature varied around 20 °C. Typical values of parameters necessary for the pTZ SGERG-88 method were as follows: the molar ratio of carbon dioxide 0.030, the molar ratio of nitrogen 0.790, the superior calorific value of natural gas 37 MJ·m^{-3} and the relative natural gas density 0.565. These quantities are measured using a chromatograph and a gas specific gravity transducer.

Table 2: Ambient temperature effect on vibrating densitometer measurement of gas density.

Insulation level	without	basic	level I	level II
Typical measured error [kg.m^{-3}]	1.00	0.15	0.10	0.03
Typical relative error [%]	2.50	0.40	0.25	0.10
Maximal measured error [kg/m^3]	0.50	0.08	0.04	0.02
Maximal relative error [%]	1.50	0.20	0.10	0.05

For a pipe 500 mm in diameter and 300 mm orifice with flange tappings, it is possible to calculate the gas flow through orifice with a difference pressure of 25 kPa. Table 3 shows the ambient temperature effect on gas flow measurement for three levels of insulation.

Table 3: Ambient temperature effect on gas flow measurement.

Quantity	Basic	level I	level II
Calculated density [kg.m^{-3}]	44.9093	44.9093	44.9093
Measured density [kg.m^{-3}]	45.0593	45.0043	44.9393
Absolute density error [kg.m^{-3}]	0.150	0.095	0.030
Relative density error [%]	0.334	0.212	0.067
Calculated flow [kg.h^{-1}]	246118	246118	246118
Measured flow [kg.h^{-1}]	246529	246378	246201
Absolute flow error [kg.h^{-1}]	410.683	260.179	82.192
Relative flow error [%]	0.167	0.106	0.033

5. CONCLUSION

The experimental results show minimal requirements for temperature insulation of the natural gas density measurement systems based on the vibrating densitometers in dependence on the required resultant measurement accuracy.

The contemporary trends in natural gas density measurement at border stations, i.e. step by step preferring of the pTZ method as the primary one, seems to be adequate to the contemporary standards of the utilised measurement technique. However, the direct gas density measurement still remains the only one independent checking method.

The future problem of the international transport of natural gas seems to be the creation of unambiguously defined technical requirements (flow calculation equation, the uniformity of the reference conditions, proper algorithm of compressibility calculation in agreement with valid European standards – e.g. the last studies show the need of shifting from the very frequently used method - AGA Nx 19 to the more precise one - SGERG 88) for the flow measuring systems based on the differential pressure principle.

REFERENCES

[1] VDI/VDE 2040 Part 2: Calculation Principles for Measurement of Fluid Flow Using Orifice Plates, Nozzles and Venturi Tubes, 1987

[2] ISO INTERNATIONAL STANDARD: ISO 12213-2: Natural gas – Calculation of compression factor, Calculating using molar-composition analysis, 1997

[3] ISO INTERNATIONAL STANDARD: ISO 12213-3: Natural gas – Calculation of compression factor, Calculation using physical properties, 1997

[4] JAESCHKE, M., HUMPHREYS, A. E.: Standard GERG Virial Equation for Field Use, GERG TECHNICAL MONOGRAPH 5, 1991

[5] ISO INTERNATIONAL STANDARD: ISO 15970: Natural gas – Measurement of properties – Volumetric properties: density, pressure, temperature and compression factor, 2008