Flow Measurement and Instrumentation 81 (2021) 102027

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

Fiscal measurement and the effects of atmospheric pressure variation: Small deviations and large risks

Carlos Eduardo R.B. Barateiro [a,*], Claudio Makarovsky [b], Jorge Gomez Sanchez [a], José Rodrigues de Farias Filho [b], Alexandre do Valle Faria [b]

[a] Department of Engineering, Estácio de Sá University, Macaé, Brazil
[b] Department of Engineering, Fluminense Federal University, Niterói, RJ, Brazil

ARTICLE INFO

Keywords:
Fiscal measurement
Flow measurement

ABSTRACT

The production and transport of liquid and gaseous hydrocarbons have always been the object of studies to improve technologies and procedures, as they involve large volumes and high-value goods. There are several procedures, rules and regulations applied to the measurement of fluid flow, but its applicability may involve significant operating costs. The balance between requirements and costs led to the use of gauge pressure transmitters instead of absolute pressure gauges and assuming a constant atmospheric pressure value for parameterization of compensation algorithms. This solution simplifies the calibration process but can potentially impact measurement uncertainties because atmospheric pressure is not constant. This work quantifies these impacts and concludes that, for gas systems operating below 2000 kPa, the use of absolute pressure transmitters or the incorporation of in-line atmospheric pressure gauges is recommended. Above this value, the effects of atmospheric pressure variation do not have as much impact, but even in these cases the final uncertainty estimate of the measured gas volume must consider this source of additional uncertainties.

1. Introduction

The production of oil and natural gas has always been highly regulated, and this is due to two main aspects: they are high-value products, and the transactions involve large volumes. Custody transfer represents the basis of commerce in this industry and involves producers, traders, and processing factories [1]. On the other hand, fiscal measurement is the focus of governments that normally own the concessions and collect royalties and taxes. In fact, accurate measurement has an important impact on the financial performance of companies and the revenues of producing countries [2].

In this context, regulations and technical standards pursue two main objectives: specify measurement systems that produce results as close as possible to the actual flow [3] and assess measurement uncertainty to determine transaction risk. In addition to these requirements, operators need to control the maintenance and operation costs of these systems, considering that metrological control is essential to ensure the reliability of results over time [4].

As the calibration of measuring system equipment is part of metrological control and has a considerable cost, the decision of measuring technologies is also made with a focus on their minimization. This aspect guides the use of pressure gauge transmitters to measure pressure in the measurement lines: absolute transmitters have a higher investment cost and require a longer and more expensive calibration process.

> As the flow calculation algorithms are implemented with absolute variables, it is necessary to add the local atmospheric pressure value to the gauge transmitter measurements. This would be a great solution if atmospheric pressure were constant. But it is not …

Thus, this work aims to analyze the impact of atmospheric pressure variation on the uncertainty of natural gas flow measurements and to present recommended actions to minimize its effects. To determine the impacts, surveys were carried out in the database of metrological stations in the largest producing areas in Brazil and simulations of operating algorithms to estimate measurement errors. These simulations were done for natural gas under typical operating conditions.

The work was divided into four parts. Section 2 presents the general

* Corresponding author.
E-mail addresses: cerbb@terra.com.br (C.E.R.B. Barateiro), cmakarovsky@id.uff.br (C. Makarovsky), jorge.gomez@semanaconsultoria.com.br (J.G. Sanchez), fariasfilho@gmail.com (J. Rodrigues de Farias Filho), avalle.faria@gmail.com (A.V. Faria).

https://doi.org/10.1016/j.flowmeasinst.2021.102027
Received 8 July 2020; Received in revised form 5 July 2021; Accepted 28 July 2021
Available online 11 August 2021
0955-5986/

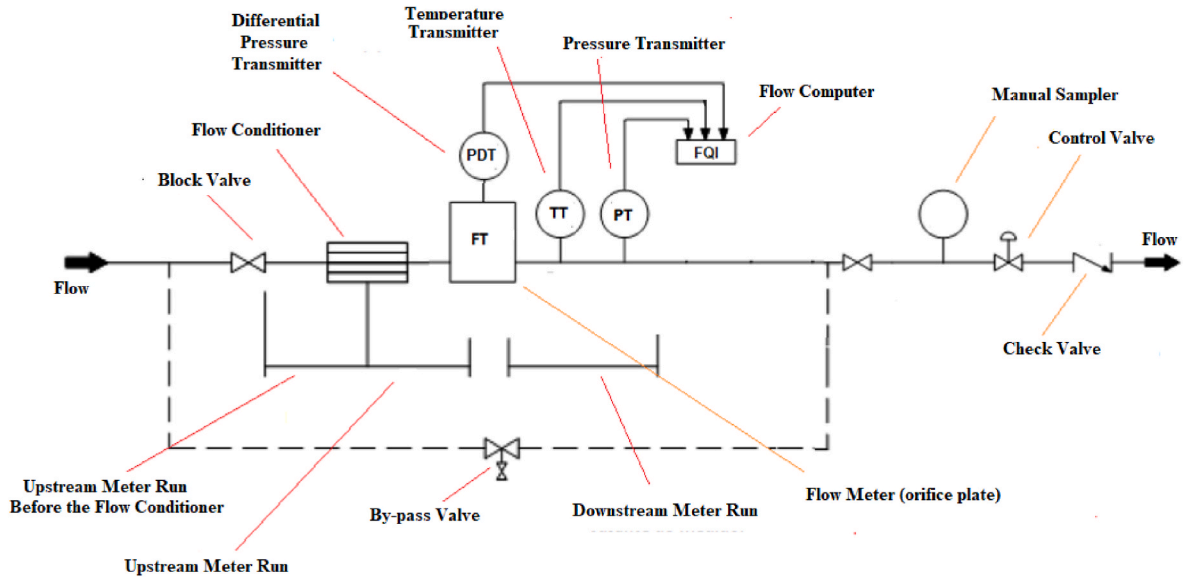


Fig. 1. Natural gas metering station using a restriction device (orifice plate).

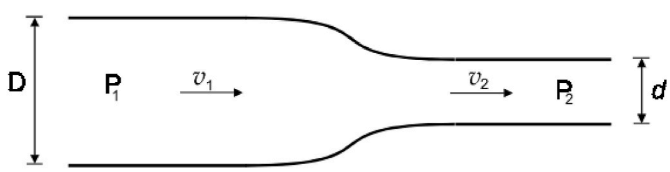


Fig. 2. Flow in horizontal tube with diameter reduction.

components of measuring stations and methods for obtaining totalized flows, Section 3 presents the results and conclusions, and Section 4 summarizes the work and presents a conclusion.

2. Metering stations aspects

Fiscal measurement must be confused with the custody transfer; in fact, tax measurement is a more general term meaning "cash measurement" which includes allocation flow measurement and custody transfer. Allocation is the numerical distribution of products between two parties according to their share of capital. Transfer of custody is a contract-driven concept: it means that there is a contractual obligation between the buyer and seller that may require adherence to standards of accuracy, repeatability, linearity, or uncertainty as defined by measurement standards [5].

Measurement standards can be divided into two large groups: a) those that originate from entities formed by industry players such as the American Petroleum Institute (API) or b) from local organizations such as the Brazilian National Metrology Institute (INMETRO). The quantification of volumes can be performed using calibrated tanks or directly measuring the flow in line and with the corresponding totalization [6].

Typically, these regulations define some aspects that must be followed by production field operators to ensure complete and accurate results (ANP, 2013), such as pressure and temperature measurement, uncorrected fluid flow and volume measurement, calculation algorithms for gas and oil, uncertainty estimation and meter calibration.

There are several approved technologies for these measurements. Fig. 1 shows the schematic of a station for measuring natural gas using a line restriction device (orifice plate). Gas composition and atmospheric pressure values can be set manually in the flow computer or by specific equipment.

In fact, all instrumentation and gauges shown in the diagrams are

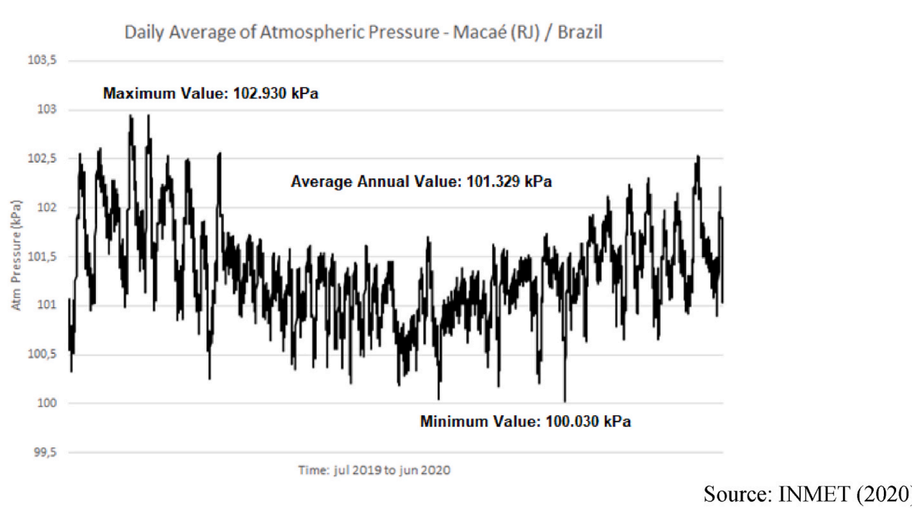


Fig. 3. Macaé daily atmospheric pressure.
Source: INMET [13].

Table 1
Typical at line condition of the gas metering station.

Component	Parameter	Value	Unit
Standard	ISO5167:2003 and AGA8:1994		
Pipe	Pipe Diameter	260.3700	mm
	Measurement Temperature	20	°C
	Material	Carbon Steel 1025	
	Thermal Coefficient	12.0.E-06	
Orifice plate	Beta	0.4270	
	Orifice Diameter	111.1700	mm
	Measurement Temperature	20	°C
	Material	Stainless Steel 316	$°C^{-1}$
	Thermal Coefficient	16.0.E-06	
Process condition	Differential Pressure Tapping	Flange	
	Differential Pressure	542	Pa
	Static Gauge Pressure	10 to 3000	kPa
	Line Temperature	50	°C
Gas composition	Methane	96.5	%
	Ethane	1.80	%
	Propane	0.45	%
	iso-Butane	0.10	%
	n-Butane	0.10	%
	iso-Pentane	0.05	%
	n-Pentane	0.03	%
	n-Hexane	0.07	%
	n-Heptane	0.00	%
	n-Octane	0.00	%
	n-Nonane	0.00	%
	n-Decane	0.00	%
	Nitrogen	0.30	%
	Carbon dioxide	0.60	%
	Water	0.00	%
	Hydrogen sulfide	0.00	%
	Hydrogen	0.00	%
	Carbon monoxide	0.00	%
	Oxygen	0.00	%
	Helium	0.00	%
	Argon	0.00	%
Normal condition	Temperature	20.00	°C
	Pressure	101.325	kPa
	Density at reference conditions	0.70	kg/m^3
	Isentropic Exponent at Normal Conditions	1.28	
	Molecular Weight of Gas	16.8036	kg/kmol
	Compressibility at Normal Conditions	0.9980	

To simulate the impacts on the measurements, the simulation software "Oil and Gas Flow Measurement Software" version V.5.2.10618.6910 issued in April 2020 from Solv Flow Measurement Company was used.

required to obtain flow rates under reference, normal or standard conditions. The most used normal assumes a temperature of 293.15 K (20 °C) and an absolute pressure of 101.325 kPa - it is also called "normal temperature and pressure condition", abbreviated as NTP [7]. Some countries, however, use International Standard Metric Conditions which consider 288.15 K (15.00 °C) and 101.325 kPa - this reference is also called the standard temperature and pressure, abbreviated as STP (ISO, 1996). For the purposes of this article, normal conditions will always be considered. For natural gas it is still necessary to correct the compressibility of the gas which is a function of the gas composition, pressure, and temperature under flow conditions.

For measuring natural gas using differential pressure sensor elements, the ISO5167 standard [8] is used, which presents a fundamental equation for obtaining instantaneous flow by the Bernoulli Equation. This equation represents energy conservation for a fluid element and its application can best be visualized in a tube with a circular cross section that is reduced in diameter as it descends in the horizontal direction, as shown in Fig. 2.

The general equation for measuring the mass flow rate used by the ISO5167 standard [8] is:

$$Q_m = \frac{C_d}{\sqrt{1-\beta^4}}\,\varepsilon\,\frac{\pi}{4}d^2\sqrt{2\Delta P\rho_1} \tag{1}$$

where $\beta = d/D$ with D is upstream diameter (m) and d is orifice or device throat diameter (m); $\Delta P = P_1 - P_2$ (Pa) with P_1 is upstream pressure and P_2 is downstream pressure; $\rho_2 = \rho_1$ (there is no change on density upstream and downstream) and Q_m is mass flow rate along the pipe (kg/s).

It is worth considering that from the equation of real gases: $\rho_2 = \rho_1 = \frac{P_2.(MM)}{Z.R.T_2} = \frac{P_1.(MM)}{Z.R.T_1}$ with MM is gas molecular mass, R is universal constant of perfect gases (8,314,462,618 J $mol^{-1}K^{-1}$), T is flowing temperature and Z is compressibility factor (depends on pressure and temperature).

Eq. (1) is derived in part from further analysis of complex theory, but it mainly comes from experimental research done over the years and presented in various publications. What is interesting about the ISO5167 (2003) standard is that it condenses all experimental research and gives it in a simple and practical way. This adaptation resulting from the experiments introduced two additional factors: Expansion Factor (ε) and Discharge Coefficient (C_d).

The Expansion Factor (dimensionless) is used to account for the fluid's compressibility, which differentiates a real fluid from a perfect gas. The numerical values of ε for orifice plates given in ISO5167-2 (2003) are based on experimentally determined data. For nozzles and Venturi tubes, they are based on the general thermodynamic energy equation. For steam and gases (compressible fluids) $\varepsilon < 1$. It is calculated with different formulas depending on device geometry. For example, for an orifice plate, ISO5167-2 gives the following formula:

$$\in\ = 1 - \left(0.351 + 0.256\beta^4 + 0.93\beta^8\right)\left[1 - \left(\frac{P_2}{P_1}\right)^{1/k}\right] \tag{2}$$

where k is the isentropic exponent, a property of the fluid that depends on the pressure and temperature of the fluid. It is related to the adiabatic expansion of the fluid in the orifice.

The discharge coefficient (dimensionless), set to a flow of incompressible fluid, relates the actual flow rate to the theoretical flow rate through a device. It is related to turbulent flow and the restriction that devices place on the flow. ISO5167-2 (2003) provides the following formula for an orifice gauge with flange taps and diameter ratio $\beta = d/D$ between 0.1 and 0.75.

$$C_d = 0.5961 + 0.0261\beta^2 - 0,216\beta^8 + 0.000521\left(\frac{10^6\beta}{Re_D}\right)^{0.7} + (0.0188 + 0.0063A)\beta^{3,5}\left(\frac{10^6}{Re_D}\right)^{0.3} + \\ + \left(0.043 + 0.080\,e^{-10L_1} - 0.123e^{-7L_1}\right)(1 - 0.11A)\frac{\beta^4}{1-\beta^4}$$

$$-0.031\left(M_2 - 0.8M_2^{\ 1.1}\right)\beta^{1.3} \tag{3}$$

Table 2
Flow rates at atmospheric pressure normal values.

Gauge static pressure (kPa)	Atmospheric pressure (kPa)	Absolute static pressure (kPa)	Dynamic viscosity at line conditions (Pa.s)	Density at line conditions (kg/m^3)	Compressibility at line conditions	Isentropic exponent at line conditions	Mass flow rate (kg/h) at k = 1.25	Mass flow rate (kg/h) at k = 1.4
10.000	101.325	111.325	1.0820E-05	0.697	0.9985	1.25/1.40	580.11	578.40
50.000	101.325	151.325	1.0820E-05	0.948	0.9979	1.25/1.40	677.35	675.66
100.000	101.325	201.325	1.0820E-05	1.263	0.9972	1.25/1.40	782.78	781.13
150.000	101.325	251.325	1.0820E-05	1.577	0.9965	1.25/1.40	874.97	873.34
200.000	101.325	301.325	1.0820E-05	1.892	0.9958	1.25/1.40	958.73	957.14
250.000	101.325	351.325	1.0820E-05	2.208	0.9951	1.25/1.40	1036.15	1034.58
300.000	101.325	401.325	1.0820E-05	2.524	0.9944	1.25/1.40	1108.06	1106.52
350.000	101.325	451.325	1.0820E-05	2.840	0,9937	1.25/1.40	1175.50	1174.00
400.000	101.325	501.325	1.0820E-05	3.157	0.9931	1.25/1.40	1239.67	1238.16
450.000	101.325	551.325	1.0820E-05	3.475	0.9924	1.25/1.40	1300.91	1299.42
500.000	101.325	601.325	1.0820E-05	3.792	0.9917	1.25/1.40	1358.97	1357.49
600.000	101.325	701.325	1.0820E-05	4.429	0.9903	1.25/1.40	1468.98	1467.53
700.000	101.325	801.325	1.0820E-05	5.068	0.9889	1.25/1.40	1571.69	1570.22
800.000	101.325	901.325	1.0820E-05	5.708	0.9876	1.25/1.40	1668.18	1666.76
900.000	101.325	1001.325	1.0820E-05	6.350	0.9862	1.25/1.40	1759.64	1758.24
1000.000	101.325	1101.325	1.0820E-05	6.994	0.9848	1.25/1.40	1846.87	1845.48
1200.000	101.325	1301.325	1.0820E-05	8.287	0.9821	1.25/1.40	2010.67	2009.31
1400.000	101.325	1501.325	1.0820E-05	9.587	0.9794	1.25/1.40	2162.89	2161.55
1600.000	101.325	1701.325	1.0820E-05	10.894	0.9767	1.25/1.40	2305.82	2304.51
1800.000	101.325	1901.325	1.0820E-05	12.208	0.9741	1.25/1.40	2441.21	2439.90
2000.000	101.325	2101.325	1.0820E-05	13.529	0.9714	1.25/1.40	2570.02	2568.74
2500.000	101.325	2601.325	1.0820E-05	16.862	0.9648	1.25/1.40	2869.52	2868.28
3000.000	101.325	3101.325	1.0820E-05	20.239	0.9584	1.25/1.40	3143.72	3142.51

Table 3
Flow rates with extreme low values at atmospheric pressure limits.

Gauge static pressure (kPa)	Atmospheric pressure (kPa)	Absolute static pressure (kPa)	Dynamic viscosity at line conditions (Pa.s)	Density at line conditions (kg/m^3)	Compressibility at line conditions	Isentropic exponent at line conditions	Mass flow rate (kg/h) k = 1.25	Mass flow rate (kg/h) k = 1.4
10.000	100.0300	110.030	1.0820E-05	0.689	0.9985	1.25/1.40	576.79	575.07
50.000	100.0300	150.030	1.0820E-05	0.940	0.9979	1.25/1.40	674.50	672.82
100.000	100.0300	200.030	1.0820E-05	1.254	0.9972	1.25/1.40	779.70	778.05
150.000	100.0300	250.030	1.0820E-05	1.569	0.9965	1.25/1.40	872.77	871.15
200.000	100.0300	300.030	1.0820E-05	1.884	0.9958	1.25/1.40	956.73	955.15
250.000	100.0300	350.030	1.0820E-05	2.200	0.9951	1.25/1.40	1034.29	1032.72
300.000	100.0300	400.030	1.0820E-05	2.516	0.9948	1.25/1.40	1106.55	1105.01
350.000	100.0300	450.030	1.0820E-05	2.832	0.9938	1.25/1.40	1173.94	1172.35
400.000	100.0300	500.030	1.0820E-05	3.149	0.9931	1.25/1.40	1238.13	1236.62
450.000	100.0300	550.030	1.0820E-05	3.466	0.9924	1.25/1.40	1299.07	1297.57
500.000	100.0300	600.030	1.0820E-05	3.784	0.9917	1.25/1.40	1357.56	1356.05
600.000	100.0300	700.030	1.0820E-05	4.421	0.9903	1.25/1.40	1467.68	1466.23
700.000	100.0300	800.030	1.0820E-05	5.059	0.9889	1.25/1.40	1570.15	1568.71
800.000	100.0300	900.030	1.0820E-05	5.700	0.9876	1.25/1.40	1667.04	1665.62
900.000	100.0300	1000.030	1.0820E-05	6.342	0.9862	1.25/1.40	1758.55	1757.15
1000.000	100.0300	1100.030	1.0820E-05	6.985	0.9849	1.25/1.40	1845.67	1844.28
1200.000	100.0300	1300.030	1.0820E-05	8.278	0.9821	1.25/1.40	2009.48	2008.13
1400.000	100.0300	1500.030	1.0820E-05	9.578	0.9794	1.25/1.40	2161.79	2160.45
1600.000	100.0300	1700.030	1.0820E-05	10.885	0.9768	1.25/1.40	2304.91	2303.59
1800.000	100.0300	1900.030	1.0820E-05	12.199	0.9741	1.25/1.40	2440.24	2438.95
2000.000	100.0300	2100.030	1.0820E-05	13.520	0.9714	1.25/1.40	2569.10	2567.81
2500.000	100.0300	2600.030	1.0820E-05	16.853	0.9648	1.25/1.40	2868.72	2867.45
3000.000	100.0300	3100.030	1.0820E-05	20.230	0.9584	1.25/1.40	3142.93	3141.72

Re_D is the Reynolds number calculated with respect to D defined as:

$$Re_D = \frac{\rho_1 \, v_1 \, D}{\mu_1} \tag{4}$$

where v_1 is the upstream velocity (m/s) and μ_1 is the fluid dynamic viscosity (Pa.s). Viscosity is a fluid property that depends on composition, pressure, and temperature.

Eq. (3) for discharge coefficient is named Reader-Harris/Gallagher Equation.

As noted, pressure measurement is essential in the process of obtaining the corrected flow and its value must be in absolute scale for gas measurement stations. The pressure value directly affects the density, expansion factor and discharge coefficient by the Reynolds number. With the use of pressure gauge transmitters, it is necessary to parameterize the local atmospheric pressure value in the flow computer.

Table 4
Flow rates with extreme high values at atmospheric pressure limit.

Gauge static pressure (kPa)	Atmospheric pressure (kPa)	Absolute static pressure (kPa)	Dynamic viscosity at line conditions (Pa.s)	Density at line conditions (kg/ m^3)	Compressibility at line conditions	Isentropic exponent at line conditions	Mass flow rate (kg/h) k = 1.25	Mass flow rate (kg/h) k = 1.4
10.000	102.9300	112.930	1.0820E-05	0.707	0.9984	1.25/1.40	584.25	582.53
50.000	102.9300	152.930	1.0820E-05	0.958	0.9979	1.25/1.40	680.91	679.23
100.000	102.9300	202.930	1.0820E-05	1.273	0.9972	1.25/1.40	785.86	784.22
150.000	102.9300	252.930	1.0820E-05	1.587	0.9965	1.25/1.40	877.73	876.11
200.000	102.9300	302.930	1.0820E-05	1.903	0.9958	1.25/1.40	961.76	960.18
250.000	102.9300	352.930	1.0820E-05	2.218	0.9951	1.25/1.40	1038.47	1036.91
300.000	102.9300	402.930	1.0820E-05	2.534	0.9944	1.25/1.40	1110.24	1108.70
350.000	102.9300	452.930	1.0820E-05	2.851	0.9937	1.25/1.40	1177.98	1176.45
400.000	102.9300	502.930	1.0820E-05	3.167	0.9930	1.25/1.40	1241.56	1240.05
450.000	102.9300	552.930	1.0820E-05	3.485	0.9923	1.25/1.40	1302.70	1301.21
500.000	102.9300	602.930	1.0820E-05	3.802	0.9917	1.25/1.40	1360.74	1359.26
600.000	102.9300	702.930	1.0820E-05	4.439	0.9903	1.25/1.40	1470.62	1469.17
700.000	102.9300	802.930	1.0820E-05	5.078	0.9889	1.25/1.40	1573.21	1571.77
800.000	102.9300	902.930	1.0820E-05	5.718	0.9875	1.25/1.40	1669.54	1668.12
900.000	102.9300	1002.930	1.0820E-05	6.360	0.9862	1.25/1.40	1761.00	1759.60
1000.000	102.9300	1102.930	1.0820E-05	7.004	0.9848	1.25/1.40	1848.17	1846.78
1200.000	102.9300	1302.930	1.0820E-05	8.297	0.9821	1.25/1.40	2011.86	2010.50
1400.000	102.9300	1502.930	1.0820E-05	9.597	0.9794	1.25/1.40	2163.99	2162.66
1600.000	102.9300	1702.930	1.0820E-05	10.904	0.9767	1.25/1.40	2306.85	2305.53
1800.000	102.9300	1902.930	1.0820E-05	12.218	0.9740	1.25/1.40	2442.06	2440.75
2000.000	102.9300	2102.930	1.0820E-05	13.539	0.9714	1.25/1.40	2570.93	2569.65
2500.000	102.9300	2602.930	1.0820E-05	16.873	0.9648	1.25/1.40	2870.52	2869.27
3000.000	102.9300	3102.930	1.0820E-05	20.249	0.9583	1.25/1.40	3144.26	3143.05

But there is a connection between oceanic tides and barometric pressure variations known as atmospheric tides that are caused by the gravity of the Earth, Sun, and Moon and even the planets of the Solar System in an insignificant margin [9]. Roden [10] and Bohm et al. [11] mention five main variation harmonics for external pressure (bi-day, day, bimonthly, monthly, and annual), astronomically justified.

3. Results and discussion

Uncertainty and a shrinking knowledge base can cost companies millions of dollars through a) Unexpected downtime when systems fail and result in loses or lost revenue; b) Increased measurement uncertainty of the system, resulting in increases in unaccounted losses; c) Non-compliance that could result in fines and/or lawsuits and d) Unnecessary travel to detect problems that result in travel costs, wasted resources and exposure to security.

With this approach, this item discusses the impacts caused on the reliability of the values determined by the measuring stations by the fact that transmitters of gauge pressure and a constant value for atmospheric pressure are used.

To assess the impact of local atmospheric pressure on the performance of these systems, the city of Macaé was chosen, located in the State of Rio de Janeiro, southeastern Brazil and very close to the Campos Basin, responsible for about 28 % of the Brazilian oil and gas production [12].

Fig. 3 shows the variation in daily atmospheric pressure occurring in the city from July 2019 to June 2020. For this period, the average value is 101.329 kPa, the lowest value is 100.030 kPa and the highest is 102.930 kPa.

The variation may appear small but the impacts on the calculation of the compensated flows are considerable.

To quantify these impacts on natural gas stations, a hypothetical measurement system was considered operating under the conditions shown in Table 1, with pressure ranging from 10 kPa to 3000 kPa (gauge).

Table 2 shows the simulation of the flow rates at the normal value of atmospheric pressure (101,325 kPa). Table 3 shows the flow rates with extreme lower limit of atmospheric pressure (100.030 kPa). Table 4 shows the flow rates with extreme maximum atmospheric pressure limit (102.930 kPa). Table 5 summarizes the error for extreme limits compared to nominal values.

NOTE: As the isentropic factor (k) changes with the gas composition and operating pressure, for simulation purposes, in Tables 2–4, k = 1.25 and k = 1.4 were used as extreme limits, chosen based on Starling and Savidge (1996). Table 5 shows the summary for k = 1.25 considering that the values for k = 1.4 are very similar.

As shown in Table 5, for the minimum value in the range of atmospheric pressure (100.030 kPa), the error in relation to the use of Normal pressure (101.325 kPa) reaches 0.573 %. With the maximum limit (102.930 kPa) this error reached −0.713 %. Even in the intermediate ranges of the simulated line pressure (500 kPa), there is 0.103 % and −0.131 %, respectively. Error rates start to drop below 0.04 % only with in-line gauge pressures above 2000 kPa, when atmospheric pressure variation has little impact. Fig. 4 graphically presents these same errors for better visualization.

The errors found for natural gas measurement systems are not negligible. For example, Brazilian legislation defines 1.5 % as the maximum uncertainty for fiscal gas measurement, so even values on the order of ± 0.1/0.2 % can impact the results.

It is noteworthy that the use of mean values for atmospheric pressure instead of the normal value (101,325 kPa) does not solve the problem. As verified in the data collected in the city of Macaé, the average atmospheric pressure value in the period considered was 101,329 kPa, which already has an impact. But the fact is that atmospheric pressure does not have the same rate of change throughout the year (there are peaks in the months of July to September, as shown in Fig. 4) and the pace of production is not constant (as shown in Fig. 5). That is, the variation in atmospheric pressure does not have the same variation as

Table 5
Error of extreme limits.

	Base value	Error analysis with minimum atmospheric pressure value		Error analysis with maximum atmospheric pressure value	
Gauge static pressure (kPa)	Mass flow rate (kg/h) k = 1.25	Mass flow rate (kg/h) k = 1.25	Mass flow rate error	Mass flow rate (kg/h) k = 1.25	Mass flow rate error
10.000	580.11	576.79	−0.573 %	584.25	0.713 %
50.000	677.35	674.50	−0.420 %	680.91	0.526 %
100.000	782.78	779.70	−0.394 %	785.86	0.394 %
150.000	874.97	872.77	−0.252 %	877.73	0.315 %
200.000	958.73	956.73	−0.208 %	961.76	0.315 %
250.000	1036.15	1034.29	−0.180 %	1038.47	0.224 %
300.000	1108.06	1106.55	−0.136 %	1110.24	0.197 %
350.000	1175.50	1173.94	−0.133 %	1177.98	0.211 %
400.000	1239.67	1238.13	−0.125 %	1241.56	0.152 %
450.000	1300.91	1299.07	−0.142 %	1302.70	0.137 %
500.000	1358.97	1357.56	−0.103 %	1360.74	0.131 %
600.000	1468.98	1467.68	−0.089 %	1470.62	0.112 %
700.000	1571.69	1570.15	−0.098 %	1573.21	0.097 %
800.000	1668.18	1667.04	−0.068 %	1669.54	0.081 %
900.000	1759.64	1758.55	−0.061 %	1761.00	0.078 %
1000.000	1846.87	1845.67	−0.065 %	1848.17	0.070 %
1200.000	2010.67	2009.48	−0.059 %	2011.86	0.059 %
1400.000	2162.89	2161.79	−0.051 %	2163.99	0.051 %
1600.000	2305.82	2304.91	−0.040 %	2306.85	0.045 %
1800.000	2441.21	2440.24	−0.040 %	2442.06	0.035 %
2000.000	2570.02	2569.10	−0.036 %	2570.93	0.035 %
2500.000	2869.52	2868.72	−0.028 %	2870.52	0.035 %
3000.000	3143.72	3142.93	−0.025 %	3144.26	0.017 %

the production curve and, therefore, the use of average values for atmospheric pressure has no effect to minimize the total error.

It is difficult to know how much of the production operates at pressure below 2000 kPa. Typically, production export systems are designed with ANSI 900 or 1500 class, to allow operation with high pressures, however other internal systems frequently operate with ANSI class 150 and 300 and therefore below 2000 kPa.

There is no specific data for the Campos Basin, but for a production of 114.37 Mm^3/d, production units in Brazil consumed 14.27 Mm^3/d for electricity generation and burned about 2.78 Mm^3/d [14]. Internal gas consumption is generally measured at pressures below 2000 kPa, equivalent to about 13 % of total gas production. With the value of natural gas at US$106,994.57/$Mm^3$ (ANP, 2020) and a typical error of 0.2 %, there is an impact of US$1.2 M per year in Brazil due to the disregard of inherent errors to the variation of atmospheric pressure in the calculation algorithms of gas measurement systems.

Obviously, station uncertainty calculations could simply consider the effects of atmospheric pressure variation to confirm that the station operates within limits but disregarding the fact that it will operate with a potential error that can be practically eliminated. Therefore, the final suggestion is that gas measurement systems operating below 2000 kPa should use absolute transmitters or have a local atmospheric pressure gauge reporting the actual atmospheric pressure in-line to the flow computers. This would be the best way to avoid the impact of this variation on the operational risk of these gas production units.

4. Conclusion

From the results presented, it is possible to conclude that the use of gauge pressure in natural gas measurement systems can generate potential errors that should not be ignored. The recommendation is that, for gas production systems operating below 2000 kPa, gas pressure measurement should always be done with absolute transmitters or in-line atmospheric pressure gauges. Above this value, the effects of atmospheric pressure variation are not as impactful, but even in these cases, the final uncertainty estimate of the measured gas volume must consider this source of additional uncertainties.

More research needs to be done to understand the real impacts of atmospheric pressure variation on crude oil measurement systems. Although the flow calculation algorithms of these systems only consider gauge pressures, it is worth remembering that absolute pressures are considered in the equations of state of the substances. Most likely, the development of flow calculation algorithms considers a simplification because liquid hydrocarbons have little compressibility, but eventually may have an impact.

It would also be interesting to go deeper into these aspects in the offshore environment. In these places, less variation is expected (Patrascu, 2018 and [11] and probably just considering errors in uncertainty calculations would be sufficient. It is noteworthy that Macaé is located on the Brazilian coast and is exactly where most of the oil operations in Brazil take place.

Obviously, the decision to install additional measuring instruments involves capital cost (purchase of instruments) and operating costs (maintenance or calibration) that must be considered.

Authorship statement

Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Drafting the manuscript, Revising the manuscript critically for important intellectual content, Approval of the version of the manuscript to be published: C.E. Barateiro, C. Makarovsky; Gomez, J.; J.R. Farias Filho; A.V. Faria. Drafting the manuscript: C.E. Barateiro, C. Makarovsky; Gomez, J.; J.R. Farias Filho; A.V. Faria.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

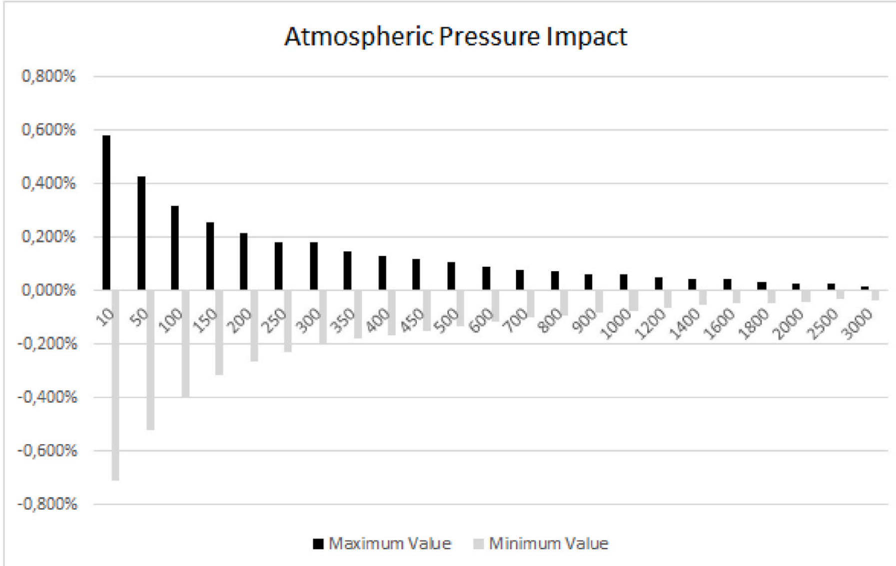
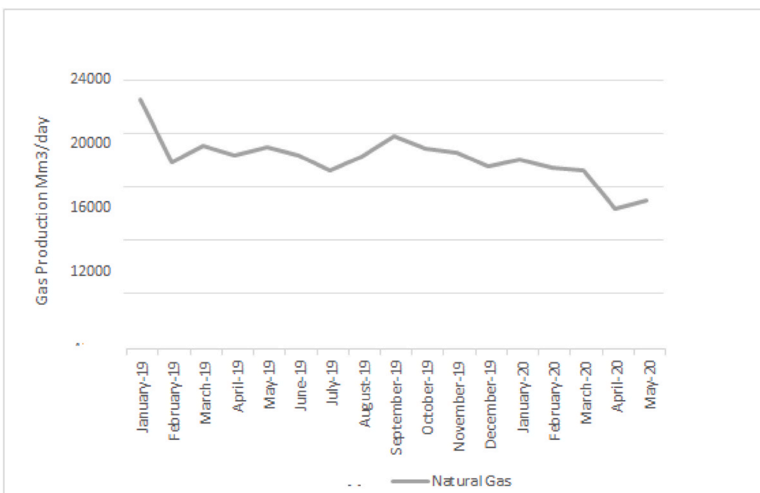


Fig. 4. Error in extreme limits for atmospheric pressure variation.



Source: ANP (2020)

Fig. 5. Campos Basin gas production.
Source: ANP (2020).

References

[1] A. Bekraoui, A. Hadjad, A. Benounah, M. Oulhadj, Uncertainty study of fiscal orifice meter used in A gas Algerian field, Flow Meas. Instrum. 66 (2019) 200–208, https://doi.org/10.1016/J.Flowmeasinst.2019.01.020, 2019.

[2] E. Dupuis, Oil and Gas Custody Transfer, when Money Changes Hands, Flow Measurement Accuracy Matters, Petroleum Africa Magazine, 2014, pp. 24–29.

[3] ANP (Agência Nacional De Petróleo), Portaria Conjunta Anp/Inmetro Nº 001, 2013.

[4] A. Soratto, O. Pohlmann Filho, M. De Paiva, R. Giordani, C. Bringhenti, Development of A system to increase the legal metrological control of measuring instruments in Brazil, Int. J. Metrol. Quality Eng. 5 (3) (2014) 304, https://doi.org/10.1051/Ijmqe/2014013.

[5] Emerson, Fiscal Measurement – Natural Gas, White Paper, Fsg-Wp-0012, 2014.

[6] S. Sivaraman, S. Ikawa, D. Comstock, Tank gauging or metering: guidelines for selection, Hydrocarb. Process. 80 (11) (2001) 85–90. Nov2001.

[7] A. Mcnaught, A. Wilkinson, in: Iupac. Compendium of Chemical Terminology, second ed., Blackwell, Scientific Publications, Oxford, 1997 https://doi.org/10.1351/Goldbook.S06036.

[8] ISO 5167-2 (International Standards Organization), Iso 5167-2:2003 Measurement of Fluid Flow by Means of Pressure Differential Devices Inserted in Circular Cross-Section Conduits Running Full — Part 2: Orifice Plates, 2003.

[9] M. Patrascu, T. Baracu, V. Badescu, M. Birsan, C. Teodisiu, M. Degeratu, E. Avram, M. Udrea, L. Calancea, C. Mesteru, Modeling air leakage in buildings caused by the cyclic variation of the atmospheric pressure, Build. Serv. Eng. Technol. 39 (4) (2018) 430–462, 2018, https://Doi-Org.Ez24.Periodicos.Capes.Gov.Br/10.1177/0143624417749536.

[10] G. Roden, On atmospheric pressure oscillations along the Pacific coast of North America, 1873–1963, J. Atmos. Sci. 22 (1965).

[11] S. Bohm, T. Nilsson, M. Shindelegger, H. Shuh, High-frequency signals of oceans and atmosphere, in: Earth Rotation Atmosphere vol. 1, Vienna University Of Technology, Tu Wien, Egu Ga, Vienna, Session G5, 2012.

[12] ANP (Agência Nacional De Petróleo), Boletim Da Produção de Petróleo E gás natural Janeiro 2020/N° 113, 2020. Access In June/2020, http://Www.Anp.Gov.Br/Arquivos/Publicacoes/Boletins-Anp/Producao/2020-01-Boletim.Pdf.

[13] INMET (Instituto Nacional De Meteorologia), Estação Meteorológica de observação de superfície automática. http://Www.Inmet.Gov.Br/Portal/Index.Php?R=Estacoes/Estacoesautomaticas, 2020.

[14] E. Ministério De Minas, Energia (Mme). Boletim Mensal De Acompanhameno Da Industria Do Óleo E Gás Natural, Departamento De Gás Natural, 2020.

Carlos Barateiro holds a BS in Mechanical Engineering at University of Campinas (1985), an MS in Civil Engineering at Fluminense Federal University (2011) and doctorate in Production Engineering also at Fluminense Federal University (2014). Technical Consultant with experience in the areas of process control, measurement, instrumentation,

automation and EPC projects and adjunct Professor and Coordinator of Civil, Mechanical and Chemical Engineering Courses at Estácio de Sá University, Macaé.

Claudio Makarovsky holds an MBA degree in Corporate Finance by FGV/Babson College and is an MS student on Management Systems at the Fluminense Federal University, with a BS chemical engineering at Oswaldo Cruz Chemical College. Claudio is Director of Manufacturing Industries at Microsoft with experience in digitalization, process control and industrial instrumentation.

Jorge Gomez has a Mechanical Engineer degree from University of São Paulo Polytechnic School and post graduate specialization in Energy & Fluids from University of Campinas. More than 30 years of experience in fluid flow and process instrumentation, working in R&D and engineering positions at IPT (São Paulo Institute for Technical Research) and international companies such as Schlumberger, Invensys, and Emerson. Since 2016 acting as Technical Independent Consultant in fluid flow measurement and process instrumentation.

José Rodrigues De Farias Filho holds a BS in Civil Engineering at University of Fortaleza (1988), Specialist degree in Occupational Safety Engineering at Fluminense Federal University (1998), MS in Civil Engineering at Fluminense Federal University (1992) and doctorate in Production Engineering also at Fluminense Federal University (1996). Farias is currently Associate Professor IV at Fluminense Federal University with experience in Production Engineering, with emphasis on Work Processes, acting mainly on the following areas: Industrial Competitiveness, Project Management; Complex Enterprises, Total Quality, Production Administration, Strategy and Organizations and Organizational Changes.

Alexandre do Valle Faria holds an MBA degree in Project Management, Master's degree in Management Systems and at this moment is concluding the doctoral program is Production Engineering, all by Fluminense Federal University. Alexandre is Procurement Manager ate Siemens with experience in supplies, ERP system, management, and business.