Influence of measurement uncertainty of associated quantities on the uncertainty of liquefied petroleum gas mass in a dynamic measurement system

Gustavo Pessanha Alvim[1, *]; **Elcio Cruz de Olveira**[1,2]

[1] Pontifical Catholic University of Rio de Janeiro, Postgraduate Program in Metrology, Rio de Janeiro, Brasil
[2] PETROBRAS S.A., Logistics, Operational Planning and Control, Measurement and Product Inventory Management, Rio de Janeiro 20231-030, Brazil
*gustavoalvim@aluno.puc-rio.br

Abstract.

Liquefied Petroleum Gas (LPG) is a versatile and widely used fuel that is crucial in various sectors. Its significance as a combustible gas stem from its high energy content and ease of storage and transportation. Its lower environmental impact than other fossil fuels further enhance its appeal as a cleaner energy alternative. This fuel finds extensive applications in industries, commercial establishments, and agricultural activities, which sheds light on its measurement systems. Based on the calculation algorithms for LPG mass, which is the trading unit of the product, and the regulatory ordinance, this study aimed to evaluate the critical factors that impact the calculation of the mass measurement in a dynamic measuring system. This work introduces the measurement function for mass calculation and the associated uncertainty calculation. Furthermore, it presents the concept and functioning of a measuring system, along with the critical factors and associated quantities, which significantly impact the calculation of the expanded uncertainty of LPG mass: correction factors for the effects of pressure, density, and temperature. Approximately, these factors have, respectively, the following weights in the total uncertainty value, based on the arithmetic average of the conducted experiments: 45 %, 43 % and 9 %. The study concludes that the prescribed uncertainty limits established by the Brazilian Institute of Metrology, Quality, and Technology regulations for secondary (or associated) quantities have limited practical significance. It occurs because all indications suggest that the uncertainty values exceeding the prescribed limit for individual uncertainty can still meet the maximum uncertainty of the output variable - LPG mass - which is the crucial aspect. Lastly, a future study to optimize individual acceptance criteria calibration is proposed.

1. Introduction

Among the various oil derivatives traded, Liquefied Petroleum Gas (LPG) stands out, as it has different physicochemical properties from other petroleum derivatives, which makes this commodity more susceptible to variations in the quantities of influence in the measurement of the transferred mass [1].

Accurate and reliable measurements are essential to ensure efficient utilization and commercial transactions. Therefore, it is essential to identify the factors that influence the calculation of LPG mass flow rate in a system and assess its associated measurement uncertainty. Some factors influence the accurate measurement of the transferred mass value of LPG, such as pressure and temperature corrections, K factor, density, pulse number, and turbine meter factor. However, not all factors have the same influence.

The pulse number represents the number of pulses generated by the turbine within the measurement interval; the K factor relates the number of pulses to volume, expressed as the number of pulses per cubic meter; and the meter factor is the relation between the gross standard quantity passed through the meter by the corresponding meter indicated volume at standard conditions.

2. The Liquefied Petroleum Gas

LPG, a valuable byproduct derived from petroleum refining processes, has emerged as a vital component in the energy sector. Typically obtained through the fractional distillation process of petroleum, it primarily comprises propane and butane. Figure 1 presents the percentage distribution of petroleum energy derivatives production.

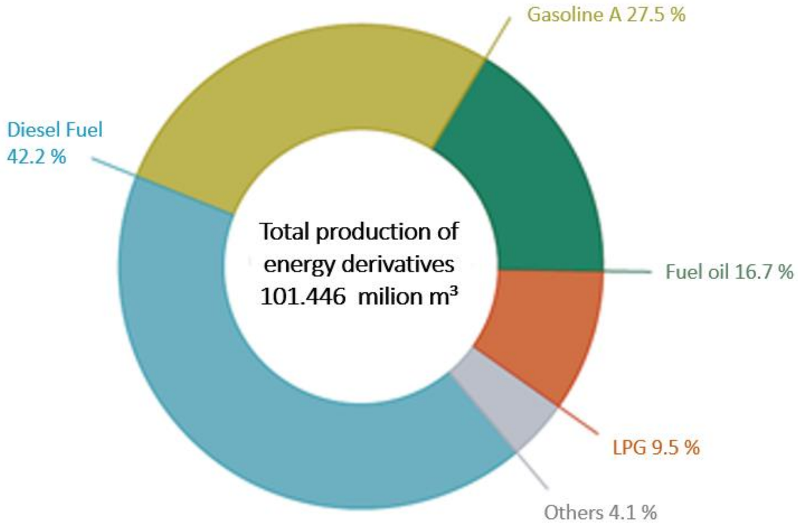

Figure 1: Total production of petroleum energy derivatives. Source: ANP [2]

Due to its high energy content, LPG is highly applicable as a fuel, finding extensive usage in domestic, industrial, commercial, and agricultural settings. In addition to its lower environmental impact compared to other fossil fuels, it also offers convenience in handling, storage, and transportation. The

Brazilian Energy Balance (BEM), published by the Energy Research Company (EPE) in 2022, indicates LPG as the third most utilized energy source in Brazilian households in 2021, Figure 2.

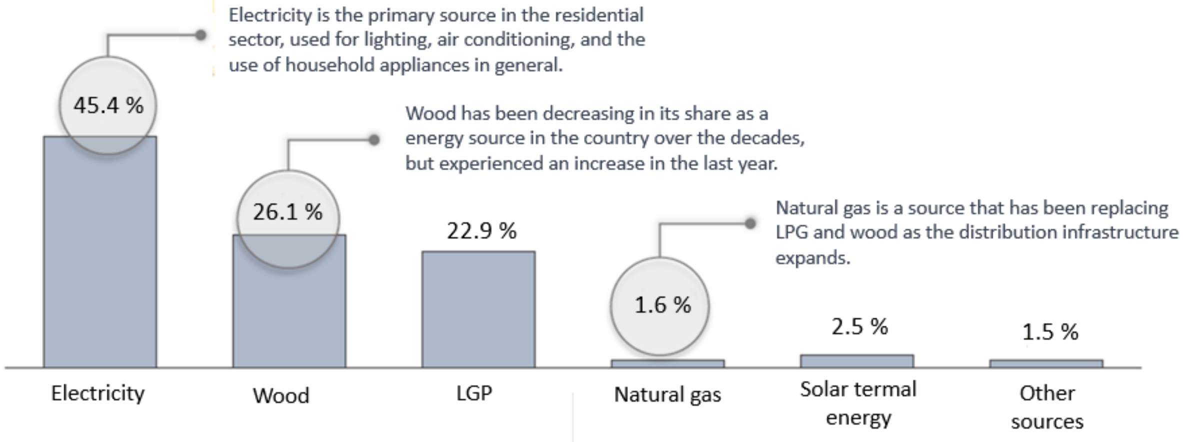

Figure 2: Brazilian residential energy matrix. Source: Balanço energético nacional [3].

3. Measurement system and Inmetro Ordinance

In this context, standards were created to ensure compliance with storage, transportation, and distribution processes. Among them, the Brazilian Institute of Metrology, Quality, and Technology (INMETRO) Ordinance No. 291, on July 7 th, 2021 [4], approved in its text the Brazilian Metrological Technical Regulation, which established minimum conditions for dynamic measurement systems of quantities of petroleum and its liquid derivatives.

Measurement systems for liquefied petroleum gases can utilize volumetric or mass determination methods, which can be applied in static and dynamic conditions. According to Oliveira [5], in Brazil, generally, LPG is measured volumetrically using turbine meters and converted to mass basis by density.

The measuring system, also known as metering stations, are responsible for measuring the flow rate and calculating the mass of LPG. The system, as depicted in Figure 3, is composed of a flow transmitter (FIT), a pressure transmitter (PIT), a temperature transmitter (PIT), a densitometer (AIT) and a flow computer (FQIT).

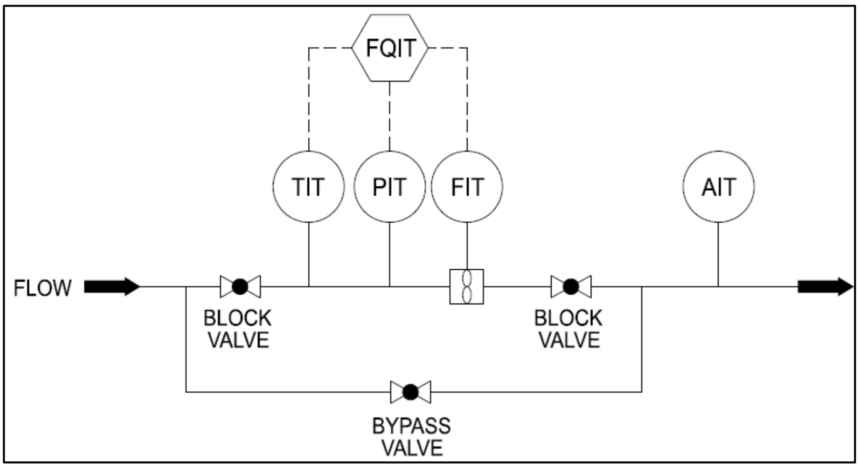

Figure 3: Schematic installation of a flow measuring station.

The equipment for measuring the system's flow rate can be a turbine meter. A turbine meter is a flow measurement device that operates based on the principle of fluid flowing through a rotating turbine. The fluid passing through the meter causes the turbine to rotate, and the speed of rotation is proportional to the flow rate. The rotation of the turbine is detected by sensors or magnets, which generate electrical pulses that are then converted into flow rate readings. Turbine meters are commonly used for measuring the flow of liquids and gases in various industrial applications due to their accuracy, wide flow range, and low pressure drop.

The measurement of gas flow occurs under unstable pressure and temperature conditions, known as operating or metering conditions, which can change for many reasons. However, the volumetric indications of transferred or received fluid must be referenced to conditions defined by regulatory bodies, known as base conditions. The base conditions are defined as a temperature of 20 °C and a static pressure of 101.325 kPa (or 1 atm).

The temperature, pressure, and density (also known as variable associated or secondary) measurements are transmitted to the correction device for converting the flow rate and the volume measured at metering conditions into a volume at base conditions.

The widely used device as a correction device, flow computer, is defined by Inmetro [6] as an electronic device capable of receiving signals from a flow meter and other associated devices, measuring under specific flow conditions, and executing the necessary calculations to convert the flow value to base conditions.

The Brazilian regulation, INMETRO Ordinance No. 291, on July 7th, 2021, is based on the International Recommendation OIML (International Organization of Legal Metrology) R 117-1 [7]. This document describes that the Maximum Permissible Error (MPE) for liquefied gases measuring systems under pressure measured at a temperature equal to or above – 10 °C is 1.0 % (included in accuracy class 1.0). Based on [1], the maximum permissible measurement error (MPE) can be converted into expanded uncertainty (U), according to Eq. (1). This value corresponds to the expanded uncertainty of the measuring system.

$$U = \frac{2 \times MPE}{\sqrt{3}} \tag{1}$$

In addition to specifying the maximum permissible error value for the measuring system, that is the calculated mass of LPG, the ordinance also establishes a MPE for measuring devices (temperature, pressure, and density), as shown in Table 1.

Table 1: MPE values covered by INMETRO Ordinance No. 291 and respective expanded uncertainties.

Measuring object	MPE	Expanded uncertainty
Measuring system (mass of LPG)	1.0 %	1.2 %
Temperature	0.5 ºC	0.6 ºC
Pressure*	5.0 %	5.8 %
Density	2.0 kg/m³	2.3 kg/m³

* The considered pressure value refers to the operating range between 1 MPa and 4 MPa, which was taken as a reference for the conducted experiments.

4. Mass uncertainty based on the measurement function

The volume calculation, based on ASTM, IP, ISO, and API-MPMS standards, relies on factors such as K factor, density, pulse number, turbine meter factor and temperature and pressure corrections. [5].

The Manual of Petroleum Measurement Standards (MPMS), in chapter 14, section 8 [8], the liquefied Petroleum Gas Measurement, presents the measurement function or mathematical model (Eq. 2) for the transferred mass, in tons. The model converts the volume to mass using the corrected density at base conditions of 101.325 kPa and 20 °C.

$$M = \frac{MF \times VCF \times CPL \times Np \times D_4^{20} *}{K} \tag{2}$$

Where:

M = Mass of LPG;
MF = Meter factor;
VCF = Correction factor for the effect of temperature on the liquid to the reference temperature;
CPL = Correction factor for the effect of pressure on the liquid to the reference pressure;
Np = Pulses number generated by the turbine during the measurement interval;
K = Conversion factor of a number of pulses to volume, it is given in number of pulses per cubic meter;
$D_4^{20} *$ = Corrected density.

Considering that the input quantities are not correlated, the combined standard uncertainty of LPG mass measurement is obtained based on ISO GUM [9], Eq. (3):

$$u_c(M) = \sqrt{\left(\frac{\partial M}{\partial MF} \times u(MF)\right)^2 + \left(\frac{\partial M}{\partial VCF} \times u(VCF)\right)^2 + \left(\frac{\partial M}{\partial CPL} \times u(CPL)\right)^2 + \left(\frac{\partial M}{\partial N_p} \times u(N_p)\right)^2 + \left(\frac{\partial M}{\partial D_4^{20} *} \times u(D_4^{20} *)\right)^2 + \left(\frac{\partial M}{\partial K} \times u(K)\right)^2} \tag{3}$$

And the degree of freedom (v_{eff}):

$$v_{eff}(M) = \frac{u_c^4(M)}{\frac{\left(\frac{\partial M}{\partial MF} \times u(MF)\right)^4}{v_{eff}(MF)} + \frac{\left(\frac{\partial M}{\partial VCF} \times u(VCF)\right)^4}{v_{eff}(VCF)} + \frac{\left(\frac{\partial M}{\partial CPL} \times u(CPL)\right)^4}{v_{eff}(CPL)} + \frac{\left(\frac{\partial M}{\partial N_p} \times u(N_p)\right)^4}{v(N_p)} + \frac{\left(\frac{\partial M}{\partial D_4^{20} *} \times u(D_4^{20} *)\right)^4}{v_{eff}(\partial D_4^{20} *)} + \frac{\left(\frac{\partial M}{\partial K} \times u(K)\right)^4}{v(K)}} \tag{4}$$

5. Results and discussion

The present study did not aim to develop the uncertainty equation but rather to present the relevance of each variable's contribution.

To verify the influence of the presented variables, an experiment based on the mathematical model was conducted. The input values for the experiments are the measurement uncertainties on the calibration of the instruments, which can be obtained from their respective calibration certificates. These uncertainties are directly linked to the sources of uncertainty used in the mathematical calculation presented in Eq. (2).

Table 2: Expanded uncertainty data for the experiment

Variable	Expanded uncertainty	Unit
Meter factor	0.00042	-
Temperature	1.0	ºC
Pressure	50.0	kPa
Density	1.0	kg/m³

The data was collected from three real measurement stations in Brazilian Northeast (table 3).

Table 3: Data for measuring stations.

Measuring Station	Variable / Factor	Value	Associated uncertainty source	Contribution on expanded uncertainty LPG Mass	Expanded uncertainty of LPG Mass
1	Meter Factor	1.0010	MF	2.76 %	0.79 %
	Temperature	24.82 ºC	VCF	13.63 %	
	Pressure	1306.7 kPa	CPL	39.34 %	
	Density	538.5 kg/m³	$D_4^{20}*$	44.26 %	
2	Meter Factor	1.0011	MF	2.83 %	0.79 %
	Temperature	22.06 ºC	VCF	6.20 %	
	Pressure	1354.1 kPa	CPL	50.30 %	
	Density	510.1 kg/m³	$D_4^{20}*$	40.68 %	
3	Meter Factor	1.0011	MF	3.12 %	0.75 %
	Temperature	19.61 ºC	VCF	6.82 %	
	Pressure	1282.4 kPa	CPL	45.22 %	
	Density	510.5 kg/m³	$D_4^{20}*$	44.84 %	

The figures below illustrate the results.

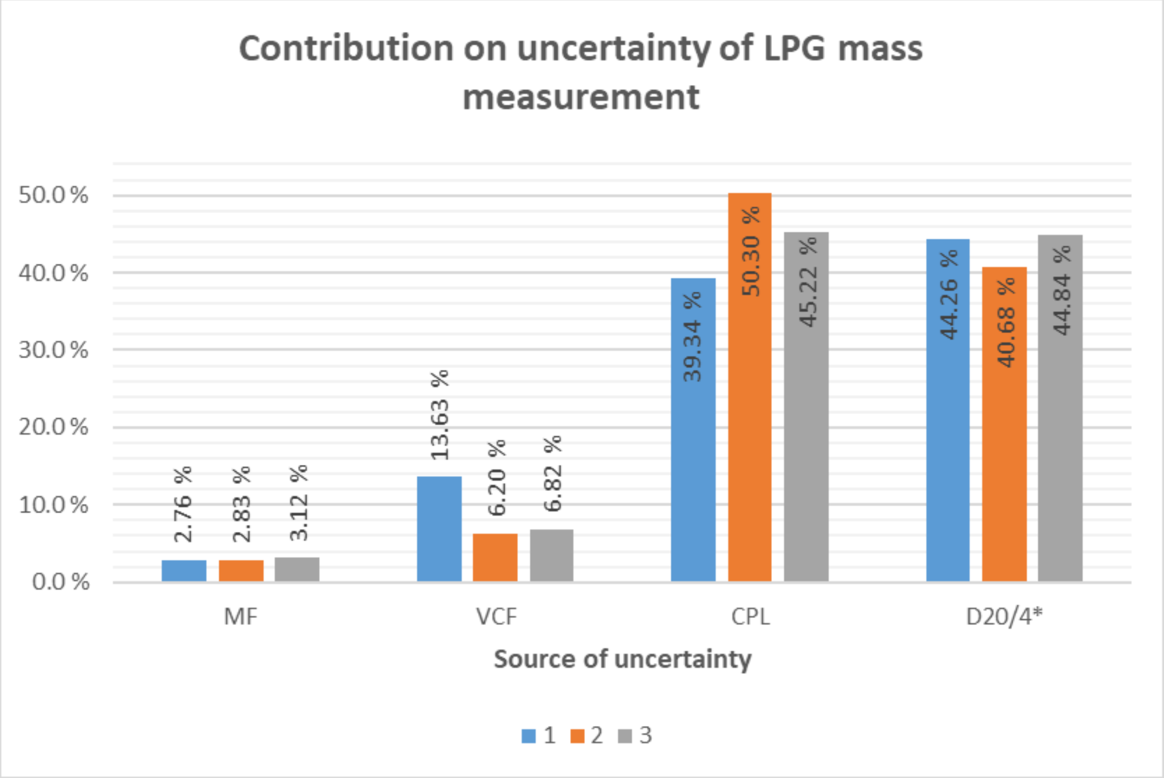

Figure 4: Contributions of MF, VCF, CPL and $D_4^{20}*$ on uncertainty of LPG mass measurement.

The contributions by measuring stations were grouped into a single table.

Table 4: Data for comparison off all measuring station.

Associated uncertainty source	Contribution on expanded uncertainty LPG Mass			
	Measuring Station nº 1	Measuring Station nº 2	Measuring Station nº 3	Arithmetic average
MF	2.76 %	2.83 %	3.12 %	2.90 %
VCF	13.63 %	6.20 %	6.82 %	8.88 %
CPL	39.34 %	50.30 %	45.22 %	44.95 %
D20/4*	44.26 %	40.68 %	44.84 %	43.26%

The experiment showed which variables are relevant to the LPG mass uncertainty. In descending order, considering the arithmetic average, the relevant contributions were the correction factor for the effect of pressure (CPL) with almost 45 %; the corrected density ($D_4^{20}*$) that overtakes 40 %; and the correction factor for the effect of temperature (VCF), that is around 10 %. Considering the low contribution value of the meter factor, the Np and K factor, were not considered relevant.

As shown in Figure 4, the contributions of the pressure, temperature, and density variables can vary significantly due to changes in process conditions. Therefore, the preliminary results indicate the potential to optimize for the values of expanded uncertainty for the associated or secondary variables, presented in Table 1. In other words, the prescribed limit values established by the regulation could be surpassed if the maximum uncertainty value for the system is respected.

6. Conclusion

The results demonstrate that the uncertainty measurement value of density, pressure, and temperature are critical for LPG mass uncertainty. On the other hand, the uncertainties of the K factor, pulses number and, turbine meter factor do not significantly impact. The method considered is the volumetric on a dynamic measurement system, which is then converted to mass by density using a standard procedure.

This study suggests that the prescribed uncertainty limits established by INMETRO regulations for secondary (or associated) quantities have limited practical significance. It occurs because even if the uncertainty values for individual quantities exceed the prescribed limits, they can still meet the maximum uncertainty requirement for the output variable, which is the critical aspect of LPG mass measurement. The use of transmitters that would initially not meet the established limits, and in this way, optimizing the acceptance criteria in the calibration of the instruments, prevents improper disposal of the equipment, providing financial, bureaucratic, and operational benefits.

Future work is being developed using Design of Experiments methodology associated with Response of Surface Methodology to optimize the individual acceptance criteria calibration of secondary transmitters of static pressure, temperature, and density as the calibration input data of a LGP measuring system.

References

[1] DE SOUZA FILHO, Pedro Lincoln; DE OLIVEIRA, Elcio Cruz; ARAMAKI, Thiago Lessa. Maximum permissible differences in LPG operations for custody transfer measurements. Measurement, v. 175, p. 109117, 2021.

[2] Anuário estatístico brasileiro do petróleo, gás natural e biocombustíveis: 2022/Agência Nacional do Petróleo,Gás Natural e Biocombustíveis. - Rio de Janeiro: ANP, 2006. Acess in November/2022, https://www.gov.br/anp/pt-br/centrais-de-conteudo/publicacoes/anuario-estatistico.

[3] Balanço energético nacional: relatório síntese 2022/ empresa de pesquisa energética. Acess in November/2022, https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-675/topico-631/BEN_S%C3%ADntese_2022_PT.pdf.

[4] Brazilian Institute of Metrology, Quality, and Technology (Inmetro), Ordinance 291, 2021.

[5] DE OLIVEIRA, Elcio Cruz. Pressure influence in LPG measurements by uncertainty evaluation. In: 2010 8th International Pipeline Conference. p. 1-8.

[6] Brazilian National Agency of Petroleum, Natural Gas and Biofuels & Brazilian National Institute of Metrology Standardization and Industrial Quality; Technical Regulations for the Measurement of Oil and Natural Gas, approved by Joint Administrative Ruling ANP/INMETRO N◦ 1, dated 10 June 2013

[7] OIML R 117-1. Dynamic measuring systems for liquids other than water Part 1: Metrological and technical requirements. Paris: OIML. BIML. 2007.

[8] A.P.I. MPMS, American Petroleum Institute, Manual of Petroleum Measurement Standards Chapter 14 – Natural Gas Fluids Measurement, Section 8 – Liquefied Petroleum Gas Measurement, ISO, Gen`eve, API, Washington, 2011.

[9] Guide to the Expression of Uncertainty in Measurement (GUM), Inmetro.Acess in June/2023, http://www.inmetro.gov.br/noticias/conteudo/iso_gum_versao_site.pdf.