METHOD OF CALIBRATION FOR TURBINE FLOW METER

Alexandre Dias Flügel, alexandre.d.fluegel@ltt.uni-erlangen.de
Lehrstuhl für Technische Thermodynamik. Friedrich Alexander Universität Erlangen-Nürnberg, Germany

Ely Vieira Cortez, evcortez@lcp.inpe.br
Marco Aurélio Ferreira, marco@lcp.inpe.br
Instituto Nacional de Pesquisas Espaciais, Rodv. Presidenre Dutra, km 40, Cachoeira Paulista - SP, 12630-000

Pedro Teixeira Lacava, placava@ita.br
Instituto Tecnológico de Aeronáutica, Pça.Mal. Eduardo Gomes, n°50, São José dos Campos - SP, 12228-900

Abstract: *Flow meters are used in order to measure the flow rate. This measuring device has an enormous economical significance in industry [1] and important task in research. Worldwide, incorrect calibrated flow meters generate fluid losses equivalent to an amount of money estimated in 10 billion US dollars per year [2]. The environmental conditions, the frequency of their use and many other factors are responsible for all instruments suffering drift in their characteristics [3, 4]. For this reason, instrument calibration becomes crucial. Calibration must be done periodically and before each experiment in order to guarantee that it can be exactly reproduced, as well as the reliability of experimental results. In the current work, we developed a calibration method for turbine flow meters in the range of 1 to 4g/s of alcohol. The calibration procedure is based on re-calibrating a commercial turbine flow meter which was firstly used to control hydrazine (N_2H_4) volumetric flow in ethanol C_2H_5OH (93%). Hydrometer, analytical balance, thermometer and thermocouple were applied together with the acquisition data system. Employing the meter in a pulsing combustion experiment which required a constant flow-correction, in situ, the partial pollutants fluctuation was measured. The entire trial process, the calculation and uncertainties are also described in detail. The calibration results for the turbine flow meter show excellent accuracy and uncertainty less than 1% in flow. The method presented in this paper is applicable to any model of flow meter.*

Keywords*: turbine flow meter, flow meter calibration.*

1. INTRODUCTION

The flow measurement means to determine the amount of liquid, gas or solid that flows in a certain place in time, for this includes the flow meter. The material quantity can be controlled per mass [kg/s] or volume unit [m^3/s], and the measurements *in situ* or by aggregation of mass or volume. In case of liquids and gases, we normally use volumetric flow meters. Most fluids are sensitive to temperature variation and normally it is not possible to control the environment temperature. The heat transfer of the pipeline is inevitable. It can be reduced with a thermal insulating material. Fluid dilation decreases the accuracy of measurement, if we can not control or correct the effect in real time.

Turbine flow meters are instruments with great precision and reliability. They present very good linearity, around 1 %, and repeatability of 0,25 %. Usually, a turbine flow meter is used in fluids of low viscosity. These devices have the same diameter of the pipeline. Its measurement module consists of a turbine that rotates on its own axis when the fluid flows by their magnetic blades. The blades movement inducts electromagnetic field, which results in Hall Effect and produces square or sine signals. The electric signals produced are proportional to the flow. While in other devices, infrared diodes are employed to detect the movement of the turbine. The turbine has a middle rotation frequency between 100 to 2000 Hz, which does not allow the measurement of low flow or initial flow. Their calibrations are necessarily for any different fluid and work conditions. Appropriate calibration is done by the manufacturer, the user needs only to choose the better instrument for his measurement. Most of turbine flow meters works in interval ratio of ten times of its speed flow, *e.g.* from 0.5 to 5 m/s. They are made of stainless steel and their components in polymers, what allow these devices to work in hostile conditions, pressure up to 250 bar and temperature between-20ºC to 90ºC. Ball-bearings and bushings ceramics or tungsten carbide are used. The good functionality of these devices requires some care in the set up, such as: (1) the flow direction of both fluid and flow meter must be the same; (2) alignment of the device with the pipeline; (3) the fluid flow must travel by turbine gradually to avoid damaging in the bearings and to eliminate all possibilities of air bubbles in the line before starting any work; (4) the rotor of turbine should be always immersed in the fluid to avoid the bubble formation; (5) if necessary, the installation of valves downstream from the meter to keep the rotor full of fluid. In order to conduct an efficient combustion process and, at the same time, to improve the fuel consumption and reduce the pollutants, it is extremely necessary for the reactions to be within the limits of the work that is determined by project of the injector and the combustion chamber. In addition, the research and development of new atomizers and combustion chambers require an excellent flow control of fuel and oxidizer.

The main problems in combustion technology regarding flow control can be mentioned as following. The mixture of fuel components is practically impossible to control, *e.g.* diesel and gasoline have hundreds different molecules in their basic formation, so it is also impossible to have different (bench) research apparatus for each different fuel, like fossil,

bio-mass, gas and others. The ideal is to use a calibration process that permits an easy exchange of the fuels, maintaining the accuracy. This paper concerns a methodology to calibrate turbine flow meters and their respectively uncertainty calculations. The method was tested experimentally at the National Institute for Space Research (INPE) and Aeronautics Technology Institute (ITA) using a commercial turbine flow meter manufactured by COX Instrument, model LF6-000, to measure hydrazine (N2H4) flow. Its re-calibration was realized for ethanol 93% (C_2H_5OH), showing flow error less than 1%. The next sections will discuss the experimental set up, the methodology employed and the development of uncertainty calculations.

The combustion and propulsion laboratories of ITA and INPE have developed new injectors and combustion chambers in last decade, with the aim of investigating the pulsating combustion, for which they have shown excellent results. In addition to this, they showed an increasing of thermal combustion efficiency as well as partial pollutants reduction [5]. The interest to bio-fuel and alcohol combustion is increasing gradually and the researches are focused on liquids fuel burning. The reliability of the results of any research regarding the measurement quality and the accuracy are only achieved with a good calibration.

2. EXPERIMENTAL SET UP

The experiment used an alcohol pressure reservoir. On the top, it contained a set of valves to supply, pressurization and relief. A needle valve was used to fine controlling of the flow. A thermocouple was installed in the pipe line, after the needle valve and before turbine flow meter. To know the fluid temperature before the metering permits us to calculate the volumetric dilation allowing correcting the value. Downstream the turbine, a gauge pressure was connected to measure the atomization pressure. In order to calibrate the turbine as function of mass flow of alcohol, the discharge flow was directed to a closed recipient positioned on a digital output balance. The system was totally closed to avoid loss of mass by evaporation.

3. CALIBRATION METHOD

The methodology was developed in order to calibrate specifically the turbine flow meter, but it can be applicable to other models of flow meters. In combustion processes the flow of fuels and oxidizers are the main variables in oxidation reaction.

The flow measurement is one of the physical properties of larger difficulty in the application of countless meters related to factors of the fluids as: density, viscosity, mass specifies, concentration and other. These properties are sensitive to the change of temperature and, in most cases, are not easy to control the temperature and variation of them. In this case, it is better to understand the experiment comportment. Then, we can calculate all variation, like we will present afterward, and through a program to correct a measurement.

The calibration is a statistical process which guarantees the reliability of the desired measurement. At first glance, a standard is necessary, together with the calibration method and a mathematical formulation that allows us to calculate the uncertainty related to the calibration and measure. A calibration method is of major importance for an experimental work for several reasons, *e.g.* the cost; it would be impracticable to have research facilities for each type of fuel, and anyway the calibration is necessary every time a new experiment begins.

The following topics explain some basic statistics concepts important to understand the methodology.

4. MEASUREMENT UNCERTAINTY

In experimental sciences, all measurement should report the physics - which represents an approximation to the true value - and its respective uncertainty. The uncertainty describes a region about an observed value, besides it is related with both the systematic and random error of the measurement, see Eq. 1. Logically, accuracy and precision of instruments also influence drastically its value. The standard deviation is a way to analyse the precision and measurement uncertainty of the repeated measure, but is correct only when the instrument is accurate. The uncertainty of a measure, w, is defined as:

$$w = \pm\left(B + t_{95}\,\sigma\right). \tag{1}$$

B is the systematic error, t_{95} is the point of the curve "Students t" that takes to 95% of certainty probability and σ is the standard deviation. The distribution of "Students t" is a distribution normal or almost normal; its curve possesses area same to 1, the test allows to calculate the number of samples (experimental data) necessary to obtain reliability in percentage (Spiegel, M., 1970).

If the number of measurements is equal or superior to 31 determinations, it is allowed to adopt:

$$w = \pm(B + 2\sigma). \tag{2}$$

The calibration process of the turbine flow meter considered the following parameters: specific mass and temperature of the alcohol, time of the experiment, frequency of the turbine and amount of mass. The specific mass was determined with a hydrometer, with a fine graduated division of 0.0005 g/cm3. The systematic error considered was 0.00025 g/cm3, calculated as the half of a graduated division. The temperature was measured with a thermocouple calibrated with a precise graduated thermometer, with precision around 0.1ºC and systematic error of 0.05ºC. The time variation was measured with the internal clock of the acquisition system. This physical dimension was adopted free of error besides of the frequency. The total mass of alcohol was measured with an analytical balance, with sensitivity of 1g. Although the systematic error is considerate normally the haft of sensitivity, by Δm an error of 1g was considered.

Tab. 1 shows the systematic error of the instruments used on turbine flow meter calibration.

Table 1. Systematic error of instruments.

Variable	*B*	Unit	Instrument
Δm	1	g	Analytical Balance
Δt	0	s	Computer
θ	0.05	ºC	Thermometer
θ	0.05	ºC	Thermocouple
ρ	0.00025	g/cm^3	Hydrometer

5. PROPAGATION OF UNCERTAINTY

A physical quantity is normally a dependent variable. It means that the results of an experiment are only reproducible on statistic control of all independent variables. The results of experimental measurements have uncertainties due to measurement limitations and systematic and random errors. For this reason, the uncertainty must be propagated considering all independent variables. Below, Eq. 4 exemplifies the uncertainty propagation of a dependent variable "r" in function of the independent variables "S_N".

$$r = r(S_1, S_2, S_3, ..., S_N). \tag{3}$$

The error propagation of the physical quantity (r) is represented by Eq. 3. The propagation is based on the statistic of a Gaussian function. The derivatives represent variations of independent or also dependent variables as functions of the physical quantities measured. The parameter "w_n" is measurement uncertainty; see Eq.´s. 1 and 2, both are function of measurement instrument.

$$w_r = \left[\left(\frac{\partial r}{\partial S_1} w_1 \right)^2 + \left(\frac{\partial r}{\partial S_2} w_2 \right)^2 + \left(\frac{\partial r}{\partial S_3} w_3 \right)^2 + ... + \left(\frac{\partial r}{\partial S_N} w_N \right)^2 \right]^{1/2}. \tag{4}$$

The equation 4 could be written in modulus, using the fluctuation of experimental data.

6. UNCERTAINTY OF SPECIFIC MASS

The hydrate ethanol, used as car fuel, has a concentration about of 93% anhydrous ethanol and 7% water. The fluctuation of ethanol concentration depends on alcohol process, ethanol storage and sometimes governmental legislation. The purchase of great quantity of alcohol was avoided due to variation of its concentration in the storage. The characterization of ethanol was carried out with hydrometer. After the measurement of the alcohol concentration through hydrometer, the specific mass depends on basically of temperature (θ). It means, $\rho = \rho(\theta)$ and it can be calculated with a simple equation, like Equation 5 and its uncertainty, Equation 6, respectively.

$$\rho = a_{\rho\theta} + b_{\rho\theta}\,\theta. \tag{5}$$

$$w_\rho = \left[\left(\frac{\partial \rho}{\partial \theta} w_\theta\right)^2\right]^{1/2} = \left[\left(b_{\rho\theta} w_\theta\right)^2\right]^{1/2}, \tag{6}$$

where w_θ is defined in Eq. (7),

$$w_\theta = w_{B\theta} + 2\sigma_\theta \tag{7}$$

The ethanol specific mass as function of the temperature was analysed between the experimental work temperatures, see Fig. 1. The data show a good linearity, and a linear function was fitted. The concentration is represented in INPM degree (92% is equivalent 92g C_2H_5OH + 8g H_20).

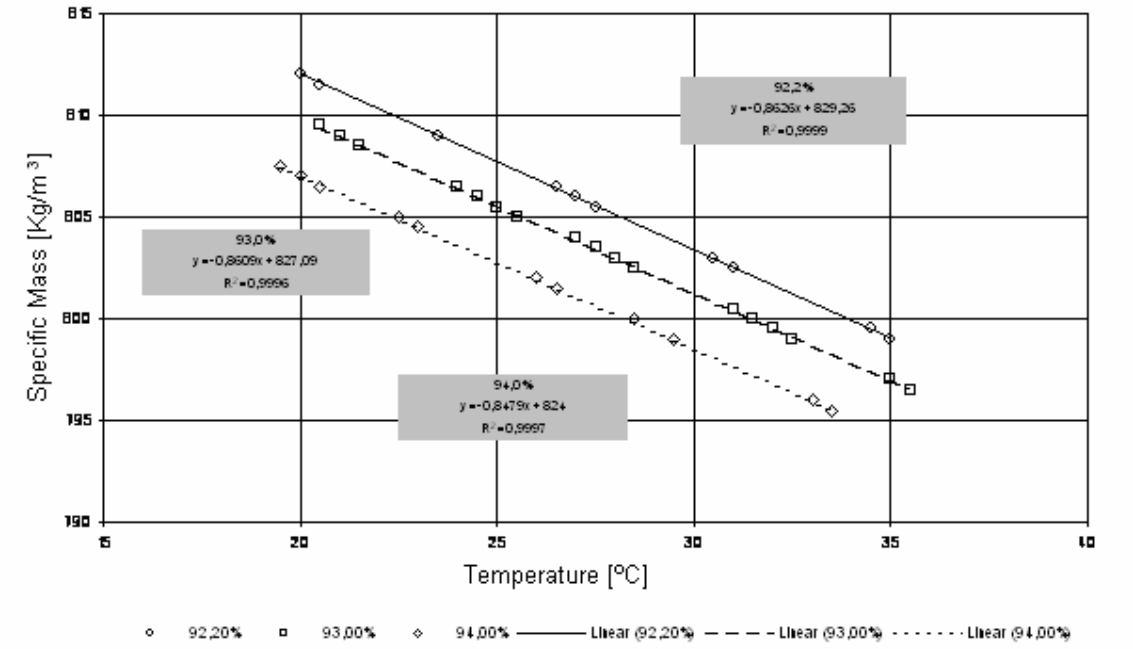

Figure 1. Specific mass variation of hydrate ethanol versus temperature.

Thus the specific mass uncertainty is calculated in accordance with Eq. 8,

$$w_\rho = \left\{\left[-0.8626\left(0.05 + 2\sigma_\theta\right)\right]^2\right\}^{1/2}, \tag{8}$$

where the systematic error of temperature $w_{B\theta} = \pm 0.05\,$ºC, from Table 1.

Though Fig. 1 shows the alcohol concentration from 92 % to 94 %, the ethanol used in the experiments presented a concentration of 92,2 %. Therefore, we adopt the coefficient $b_{\rho\theta} = -0.8626$.

7. UNCERTAINTY IN ALCOHOL QUALITY

Quality (τ) is the name used to represent the anhydrous ethanol and water ratio, in INPM degree. A conversion table from specific mass of ethanol to INPM degree can be found in any chemistry handbook. The hydrate ethanol quality is determined through the hydrometer and the correct temperature from thermometer. It means the quality is dependent of temperature and density, $\tau = \tau\left(\rho_{ref}, \theta_{ref}\right)$, and its uncertainty is calculated with the Eq. 9,

$$w_\tau = \left[\left(\frac{\partial \tau}{\partial \rho_{ref}} w_{\rho_{ref}}\right)^2 + \left(\frac{\partial \tau}{\partial \theta_{ref}} w_{\theta_{ref}}\right)^2\right]^{1/2}. \tag{9}$$

The quality variation as a function of specific mass for three different temperatures can be seen in Fig. 2. The linear correlation is represented for Eq. 10, below.

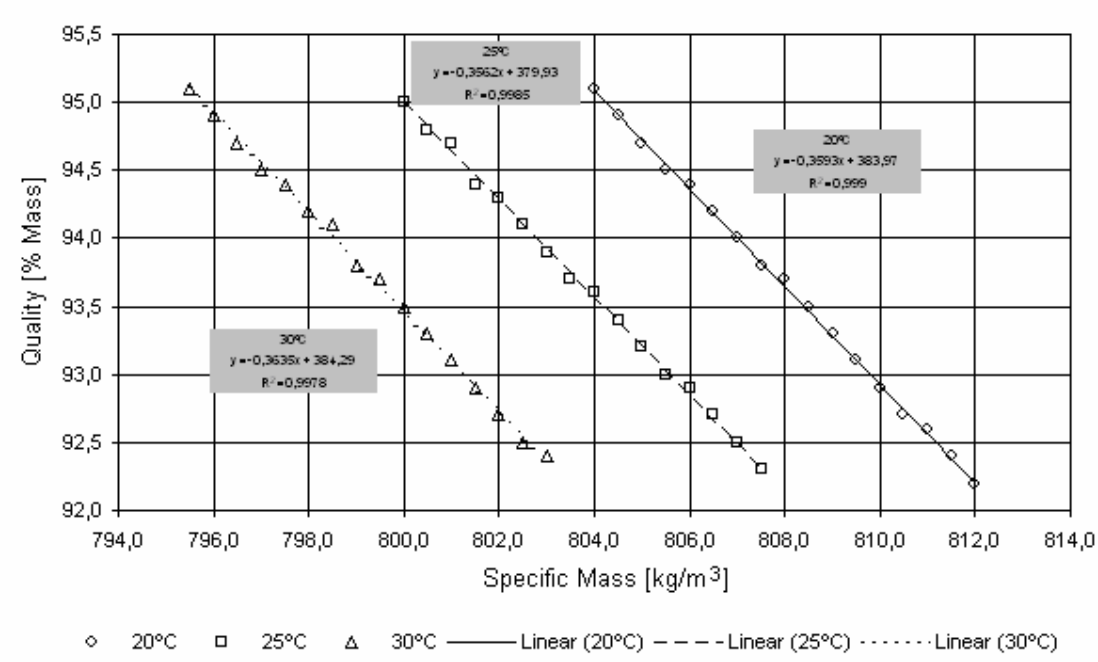

Figure 2. Quality and specific mass variation of hydrate alcohol as a function of experimental temperature interval.

$$\tau = a_{\tau\upsilon} + b_{\tau\rho}\,\rho_{ref} \,. \tag{10}$$

The quality also changes linearly with the temperature and specific mass. Fig. 3 show us the quality results for three different specific mass, which were more common in the experiment.

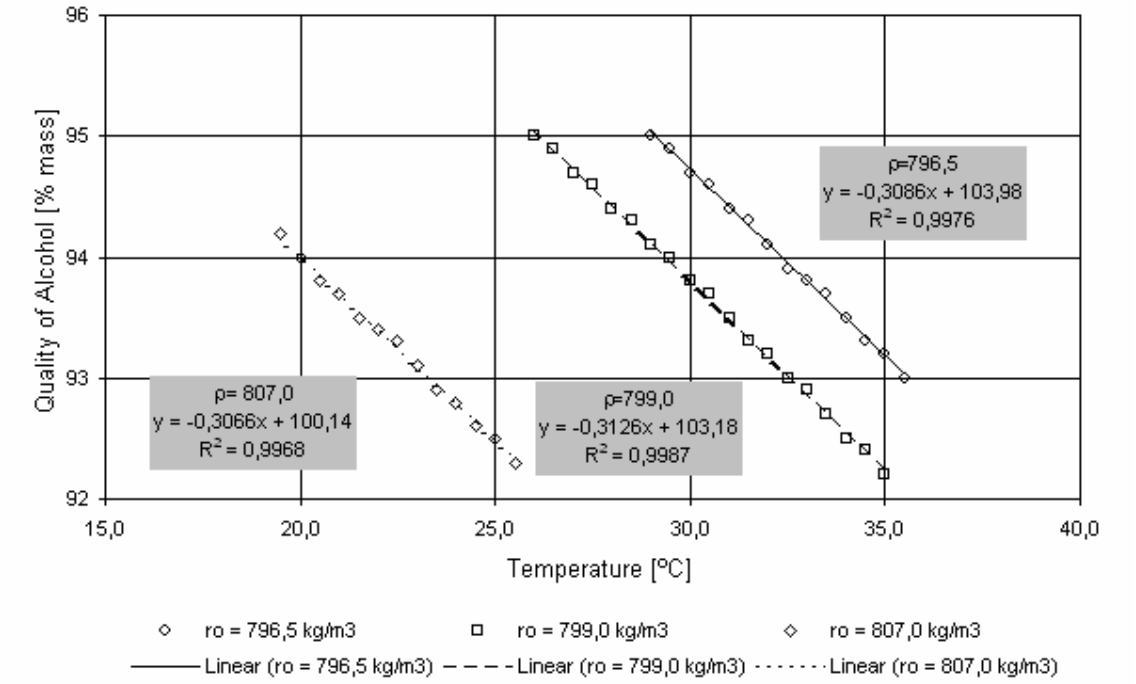

Figure 3. Quality and temperature variation of hydrate alcohol in function of specific mass interval.

Thus, the linear equation of quality as function of temperature can be written as Eq. 11.

$$\tau = a_{\tau\theta} + b_{\tau\theta}\,\theta_{ref}\,. \tag{11}$$

Due to Eq.`s. (9) to (11) and using the values $w_{\rho real} = 0.25$ kg/m^3, $w_{\theta real} = 0.05$ ºC, $\frac{\partial \tau}{\partial \rho_{real}} = -0.3635$ e $\frac{\partial \tau}{\partial \theta_{real}} = -0.313$,

The uncertainty of Alcohol Quality is calculated for Eq. 12, obtaining a error less than 0.1.

$$w_\tau = \left[(-0.3635x0.25)^2 + (-0.313x0.05)^2\right]^{1/2} = 0.1. \tag{12}$$

8. UNCERTAINTY IN ALCOHOL VOLUMETRIC FLOW

The flow meter turbine was calibrated as function of the mass flow *versus* time and frequency of turbine. The ethanol flow temperature was measured with thermocouple installed before the flow meter so that we can determine the specific mass through the interpolation of both graphs below or just use the equations. Tab. 2 show us the results of calibration

Table 2. Data and Condition of Flow Meter Calibration with Hydrate Ethanol

P_{Tanque} [kgf/cm^2]	$P_{Injetor}$ [kgf/cm^2]	Freq. [Hz]	w_f [Hz]	$\dot{m}$ [g/s]	$w_{\dot{m}}$ [g/s]	ρ [g/cm^3]	$\dot{Q}$ [cm^3/s]	θ [ºC]	w_θ [ºC]
2,0	1,0	361,1	2,8	1,123	0,006	0,8068	1,393	23,2	0,4
3,0	2,0	494,3	4,0	1,534	0,007	0,8067	1,905	23,3	0,3
4,0	2,7	585,1	4,5	1,789	0,008	0,8066	2,223	23,4	0,3
5,0	3,6	672,4	5,7	2,065	0,009	0,8066	2,553	23,4	0,3
6,0	4,6	762,9	6,3	2,326	0,010	0,8065	2,877	23,5	0,2
7,0	5,5	829,9	7,6	2,525	0,009	0,8065	3,123	23,5	0,3
8,0	6,3	889,9	6,1	2,708	0,010	0,8065	3,351	23,6	0,3

Obs.: w_{PT} = 0.1 kgf/cm^2 , w_{PI} = 0.1 kgf/cm^2

In order to understand better the Tab. 2: the ethanol was stored in a pressurized tank; see the first column of Tab. 2. We notice that until the alcohol achieves the injector, the impedance of line produced a pressure loss of at least 1 kgf/cm^2. The mass flow was controlled with the tank pressure and a fine adjustment was carried out through a needle valve. The frequencies of turbine (Freq.) were acquired and its uncertainties (Wf) calculated. Mass flow was measured with a balance, which precision was about the same of its sensitivity of 0.5g. Than, to calculate the mass flow uncertainty ($\dot{m}$), it was considered a balanced systematic error of 1g/500s. The acquisition system could calculate the ethanol density through the measurement of temperature in accordance with the explanation above.

The volumetric flow is a function of mass flow ($\dot{m}$), density (ρ) and frequency (f), as shown below:

$$Q = Q(\dot{m}, \rho, f). \tag{13}$$

The correlation of volumetric flow with mass and specific mass is written as:

$$Q = \frac{\dot{m}}{\rho(\theta)}, \tag{14}$$

and the correlation of frequency can be fitted with the graphics, see Fig. 4 and Eq. (15).

$$Q = 0{,}0717 + 0{,}0037\,f\,. \tag{15}$$

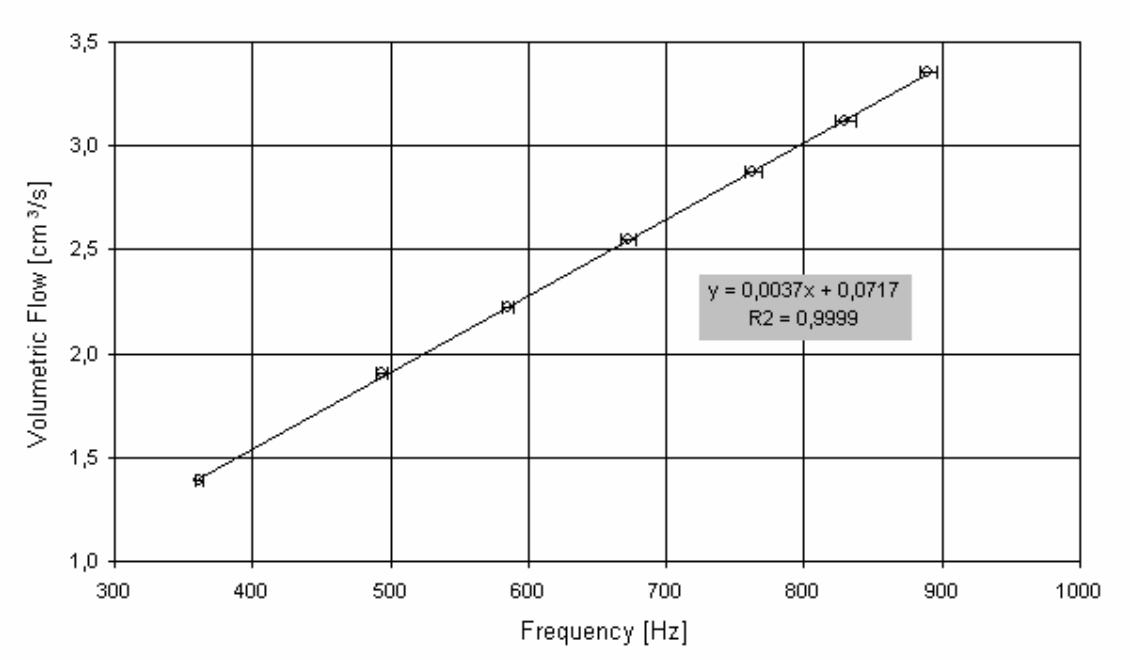

Figure 5. Turbine Frequency Versus Volumetric Flow.

Than, the uncertainty in volumetric flow is represented in Eq. (16),

$$w_Q = \left[\left(\frac{\partial Q}{\partial \dot{m}} w_{\dot{m}} \right)^2 + \left(\frac{\partial Q}{\partial \rho} w_\rho \right)^2 + \left(\frac{\partial Q}{\partial f} w_f \right)^2 \right]^{1/2}, \tag{16}$$

whose partial derivatives, found from the above function, are

$$\frac{\partial Q}{\partial \dot{m}} = \frac{1}{\rho(\theta)}; \qquad \frac{\partial Q}{\partial \rho} = -\frac{\dot{m}}{\rho^2}; \qquad \frac{\partial Q}{\partial f} = 0.0037\,. \tag{17}$$

The uncertainty in density is calculated with Eq. 6, and the other errors are shown in Tab. 2. In this calibration the measured temperature was 24.3ºC and the specific mass 0.8060g/cm^3. Linear interpolation got the value for alcohol quality of about 93.1% and was fitted to the graph of Fig.5, which show the linear behaviour of specific mass as function of the temperature for a quality of 93.1%.

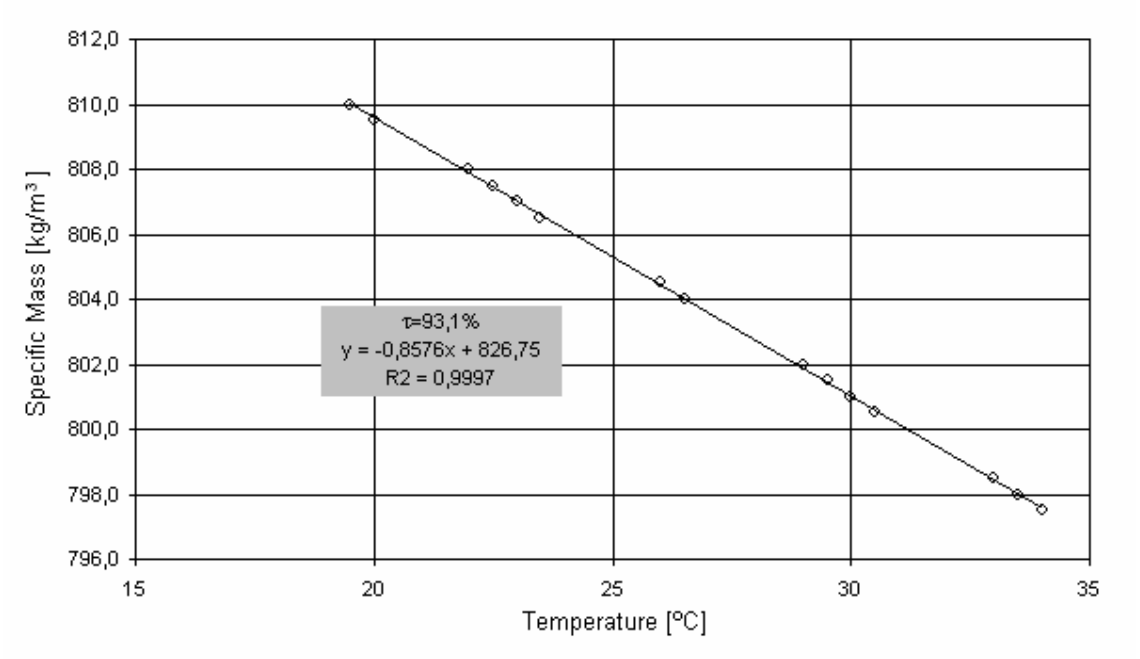

Figure 5. Relation ship between specific mass and temperature for a fix ethanol quality of 93.1%.

The function fitted from Fig. 5, showed a angular coefficient of -0.8576. Thus, the uncertainty in density is calculated with Eq. 17.

$$w_\rho = \left[\left(-0.8576\, w_\theta\right)^2\right]^{1/2}. \tag{18}$$

Tab. 3 shows a collection of numerical values for each important variable to be used in the calculation of the volumetric flow error. The volumetric flow uncertainty varies between 0.77% e 0.97% for 1.393 e 3.351 cm^3/s, respectively. In this case, we adopt an error of 1%. In literature we can find a smaller error than measured here for bigger volumetric flow. *e.g.* 1l/min to 2000l/min. But we should consider that a small turbine is complicated to build and the measured volume competes with the volume of alcohol.

Table 3. Variables and Uncertainties for Flow of Turbine.

Freq. [Hz]	w_f [Hz]	$\dot{m}$ [g/s]	$w_{\dot{m}}$ [g/s]	ρ [g/cm³]	w_ρ [g/cm³]	θ [ºC]	w_θ [ºC]	$\frac{\partial Q}{\partial \dot{m}}$	$\frac{\partial Q}{\partial \rho}$	$\frac{\partial Q}{\partial f}$	$\dot{Q}$ [cm³/s]	$w_{\dot{Q}}$ [cm³/s]	$w_{\dot{Q}}$ [%]
361,1	2,8	1,123	0,006	0,8068	0,0003	23,2	0,4	1,2395	-1,7267	0,0037	1,393	0,013	0,90
494,3	4,0	1,534	0,007	0,8067	0,0002	23,3	0,3	1,2396	-2,3612	0,0037	1,905	0,017	0,89
585,1	4,5	1,789	0,008	0,8066	0,0003	23,4	0,3	1,2397	-2,7558	0,0037	2,223	0,020	0,88
672,4	5,7	2,065	0,009	0,8066	0,0002	23,4	0,3	1,2398	-3,1651	0,0037	2,553	0,024	0,94
762,9	6,3	2,326	0,010	0,8065	0,0002	23,5	0,2	1,2399	-3,5674	0,0037	2,877	0,027	0,93
829,9	7,6	2,525	0,009	0,8065	0,0002	23,5	0,3	1,2400	-3,8721	0,0037	3,123	0,030	0,97
889,9	6,1	2,708	0,010	0,8065	0,0002	23,6	0,3	1,2400	-4,1549	0,0037	3,351	0,026	0,77

9. UNCERTAINTY IN ALCOHOL MASS FLOW

We can calculate the mass flow error through Eq´s. (19) and (20), respectively. All parameters were discussed before:

$$\dot{m} = \rho\, \tau\, Q\,; \tag{19}$$

$$w_{\dot{m}}^2 = \left(\frac{\partial \dot{m}}{\partial \rho} w_\rho\right)^2 + \left(\frac{\partial \dot{m}}{\partial \tau} w_\tau\right)^2 + \left(\frac{\partial \dot{m}}{\partial Q} w_Q\right)^2 . \tag{20}$$

Taking the derivative of Eq. (19), we get Eq. (21),

$$w_{\dot{m}}^2 = (\tau Q w_\rho)^2 + (\rho Q w_\tau)^2 + (\tau \rho w_Q)^2 . \tag{21}$$

The errors in specific mass and quality were already discussed previously. It is important to remember that Wρ varies with the temperature. Thus it is always recommended to fit a function of temperature and quality of fuel, because it decreases the total uncertainty. According to our studies, we show again Eq`s. (7) and (12), specific mass and quality error, respectively:

$$w_\rho = \left\{\left[-0.8626(0.05 + 2\sigma_\theta)\right]^2\right\}^{1/2}, \tag{22}$$

$$w_\tau = \left[(-0.3635x0.25)^2 + (-0.313x0.05)^2\right]^{1/2} = 0.1\ \% \tag{23}$$

and, finally, the mass flow uncertainty,

$$w_{\dot{m}} = \left\{\left\{\tau Q\left[0.8626(0.05 + 2\sigma_\theta)\right]\right\}^2 + \left(\frac{0{,}1}{100}\rho Q\right)^2 + (0.01\tau\rho Q)^2\right\}^{1/2} . \tag{24}$$

Considering, for example, the data obtained during the calibration, see Tab. 4, the values expected for future measurements.

Table 4. Mass flow uncertainty during the turbine calibration.

θ [ºC]	w_θ [ºC]	ρ [g/cm³]	w_ρ [g/cm³]	τ	w_τ	$\dot{Q}$ [cm³/s]	$w_{\dot{Q}}$ [cm³/s]	$\dot{m}$ [g/s]	$w_{\dot{m}}$ [g/s]	$w_{\dot{m}}$ [g/s]
23,2	0,4	0,8068	0,0003	0,931	0,001	1,393	0,013	1,046	0,011	1,007
23,3	0,3	0,8067	0,0002	0,931	0,001	1,905	0,019	1,430	0,014	1,006
23,4	0,3	0,8066	0,0003	0,931	0,001	2,223	0,022	1,669	0,017	1,006
23,4	0,3	0,8066	0,0002	0,931	0,001	2,553	0,025	1,917	0,019	1,006
23,5	0,2	0,8065	0,0002	0,931	0,001	2,877	0,028	2,160	0,022	1,006
23,5	0,3	0,8065	0,0002	0,931	0,001	3,123	0,031	2,345	0,024	1,006
23,6	0,3	0,8065	0,0002	0,931	0,001	3,351	0,033	2,516	0,025	1,006

10. CONCLUSION

Errors of flow measurements represent too many losses for companies. About billions of US dollars worldwide are expended every year in these processes, which require mass or volume flow control. Norms and standards should be used in order to achieve the minimal error and desirable accuracy. This work presented a method for calibration of turbine flow meter, which can be used any other meter calibration. Basic concepts of error and uncertainty propagation were discussed, besides of instrumentation and the possibility to use a hydrazine flow meter to measure alcohol flow. All calculations are presented step by step, and after the most important analysis follow a discussion. The final uncertainty for volumetric flow was achieved with less than 1% uncertainty. We should consider that mass flow was around 1.4g/s for alcohol and for this flow the error presents very good values, less than 1%. Another flow meter can give more precisely the measurement only for bigger flow, *e.g.* 1 to 1000 l/min.

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