DEVELOPMENT OF A METHODOLOGY FOR CALIBRATING A TURBINE METER USED FOR MEASURING THE DISPLACED AIR VOLUME AND DETERMINATION OF ITS UNCERTAINTY OF MEASUREMENT

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Abstract. *The calibration and the uncertainty of measurement procedures of the displaced gas volume by a turbine meter are not completely described in the existing standards. For this reason, a methodology had to be developed for standardizing the processes used to qualify and to analyze the results of the performance tests in a calibration facility, and to estimate the uncertainty of measurement. The temperature and pressure of air, used as a working fluid, together with the turbine signal, were measured in an existing facility of a calibration laboratory, which is being accredited by the Brazilian Calibration Network (RBC) with the developed methodology. The calibration procedure starts by calculating the ratio between the output from the master turbine, traceable to Brazilian standards, and the indicated value of the turbine under calibration . A meter factor (MF) was then calculated through the multiplication of this ratio by a correction factor, obtained from gas equations, to convert the measured volumes to temperature and pressure reference conditions. Then, the set of meter factors, calculated at different flow rates, was fitted by polynomials by a least square method, minimizing the uncertainty of calibration. A procedure was developed to take into account this dispersion in the uncertainty of measurement of the volume measured by the turbine under calibration.. A contribution of this paper is also the analysis of the influence of the proved volume of air on the accuracy of calibration.*

Keywords*:Turbine meter, Calibration Procedure, Uncertainty of Measurement*

1. INTRODUCTION

In the last years, measurement has been a matter of concern to industries, interested in improving the quality and control of their products. The National Agency of Petroleum, Natural Gas and Biodiesel (ANP) issued in 19.06.2000 the # 1 Joint Decree with the National Institute of Metrology, Standardization and Industrial Quality – INMETRO , providing legal means for establishing technical conditions and minimum requirements for a petroleum and natural gas measurement systems to operate in order to guarantee the accuracy of measurement. According to this document, all gas meters must be calibrated periodically by an accredited laboratory so that the metrological control requirements be attained, as established by INMETRO.

Today, in Brazil, there is a small number of accredited laboratories to the Brazilian Calibration Network for flow rate calibration. The reason for this fact is probably due to technical requirements and not the implementation of the laboratory management requirements (Gomes, 2005). The investment in equipments is high and there is a lack of qualified personnel. Also, the calibration methodology is not well established and there are no clear directions for constructing the calibration facility and processing the data. Moreover, the calibration and the uncertainty of measurement procedures of the displaced gas volume by a turbine meter are not completely described in the existing standards.

The CTGAS facility was sized to work in the 0.2 to 4000 m³/h range for calibrating 1 ½ “ to 12 “ diameter meters, using air as the working fluid. A facility is being built to work with natural gas.

The IPT facility was sized to work in the 6 to 3000 m³/h range, using air as the working fluid. A facility is being built to work with natural gas.

The TRANSCONTROL facility, in which this research was conducted, was sized to work in the 15 to 3000 m³/h range for calibrating 2” to 12” diameter meters, using air as the working fluid

The contribution of this paper is to develop a methodology for standardizing the processes used to qualify and to analyze the results of the performance tests in a calibration facility, and to estimate the uncertainty of flow rate measurement with a turbine meter.

2. THEORETICAL BACKGROUND

2.1 Turbine calibration

A turbine meter is a positive displacement device that measures the volumetric flow rate of a fluid as it moves through its wheel body, which rotates as a function of the displaced volume. A pulse is emitted at every turbine revolution. By counting the number of pulses per unit time it is possible to calculate the volumetric flow rate of the fluid (Q), which multiplied by the fluid specific mass (ρ) results in the mass flow rate ($\dot{m}$).

$$\dot{m} = \rho.Q \tag{1}$$

It is usual to express the volumetric flow rate at reference temperature and pressure conditions, respectively, T_0 = 293.15 K (20 °C) and P_0 = 101325 Pa. This means that a correction must be made to convert the real fluid volume (V) to the reference conditions (V_0), by using the real gas law.

$$V_0 = V.\left(\frac{P}{P_0}\right).\left(\frac{T_0}{T}\right).\left(\frac{Z_0}{Z}\right) \tag{2}$$

where Z is the compressibility factor. When measuring the flow rate with the turbine, the ratio between volumetric flow rate at reference conditions (Q_0) and at real conditions (Q) is equal to (V_0 / V).

$$\frac{Q_0}{Q} = \frac{V_0}{V} \tag{3}$$

Also, the mass flow rate at the reference conditions is the same as in real conditions.

$$\dot{m} = \rho.Q = \rho_0.Q_0 \tag{4}$$

During the calibration, both test and master turbines are placed in series. Therefore, the fluid mass flow rate is the same across them. However, the test turbine may be indicating a slightly different value. A meter factor (MF) is then defined as the ratio between the mass flow meter at the master turbine ($\dot{m}_M$) and at the test turbine ($\dot{m}_T$). Using Eq. (1),

$$MF = \frac{\rho_M.Q_M}{\rho_T.Q_T} = \frac{Q_M.P_M.Z_T.T_T}{Q_T.P_T.Z_M.T_M} \tag{5}$$

Beacause of the fact that the two turbines are placed in series and there is a small difference in flow temperature and pressure across them, the compressibility factor is approximately the same, and Eq. (5) becomes :

$$MF = \frac{\rho_M.Q_M}{\rho_T.Q_T} = \frac{Q_M.P_M.T_T}{Q_T.P_T.T_M} \tag{6}$$

In order to smooth out the fluctuations, the meter factor was calculated by integrating the values obtained from flow rate measurement. In practice, this was done by calculating the ratio between the measured air volumes through both meters over a given period of time, as calculated from the proven air volume through both turbines, directly displayed by the meters by the number of generated pulses.

It is interesting to observe that the meter factor may be also calculated as the ratio between the volumetric flow rate at the reference conditions across the master turbine (Q_{0M}) and the test turbine (Q_{0T}), using Eq. (6). When in operation, therefore, the real volumetric flow rate at the reference conditions can be calculated by multiplying the meter factor by the indicated volumetric flow rate by the test meter at the reference conditions.

As a result of the calibration, a set of pairs (meter factor-MF/ test turbine volumetric flow rate at standard conditions - Q_{0T}) is available. When measuring flow rate with the turbine, there is a need of interpolation to obtain the meter factor from the calibration data.. This can be done by fitting up to a third degree polynomial to the above pairs of points by the least square method. In operation, measuring the flow rate and using Eq. (7), the meter factor can be calculated.

$$MF = a_0 + a_1.Q_{0T} + a_2.Q_{0T}^2 + a_4.Q_{0T}^3 \tag{7}$$

2.2 Uncertainty of flow rate measurement with the turbine

2.2.1 Uncertainty of the meter factor

According to (ISO GUM, 1995), the uncertainty of measurement of the flow rate can be estimated by first of all obtaining from calibration certificates the expanded uncertainties *U* for a given coverage factor and dividers. In this paper, 95,45 % level will be used (k=2).

- U_M : Uncertainty of master turbine volumetric flow measurement. (Divider = 2)
- U_T : Resolution of the test turbine. (Divider = $\sqrt{3}$)
- U_{PM} : Uncertainty of pressure measurement at the master turbine. (Divider = 2)
- U_{PT} : Uncertainty of pressure measurement at the test turbine. (Divider = 2)
- U_{TM} : Uncertainty of temperature measurement at the master turbine. (Divider = 2)
- U_{TT} : Uncertainty of temperature measurement at the test turbine. (Divider = 2)

The standard uncertainty *u* can be obtained from Eq. (8).

$$u = \frac{U}{Divider} \tag{8}$$

The combined standard uncertainty of the meter factor (u_{MF}) can be calculated from (ISO GUM, 1995) by :

$$\frac{u_{MF}}{MF} = \sqrt{\left(\frac{u_M}{Q_M}\right)^2 + \left(\frac{u_T}{Q_T}\right)^2 + \left(\frac{u_{PM}}{P_M}\right)^2 + \left(\frac{u_{TM}}{T_M}\right)^2 + \left(\frac{u_{PT}}{P_T}\right)^2 + \left(\frac{u_{TT}}{T_T}\right)^2} \tag{9}$$

2.2.2 Uncertainty of the curve fit

The uncertainty of the curve fitting can be calculated as the root mean square deviation (u_{fit}) of the meter factor.

$$u_{fit} = \sqrt{\frac{1}{N-1} . \sum_{i=1}^{N} \left(MF_i - MF(Q_{0T,i})\right)^2} \tag{10}$$

where $MF(Q_{0T,i})$ can be calculated from Eq. (7), using the corrected measured value $Q_{0T,i}$.

2.2.3 Overall uncertainty of the meter factor (*U*)

$$u = \sqrt{u_{MF}^2 + u_{fit}^2 + (c_{0T} . u_{Q_{0T}})^2} \tag{11}$$

$$c_{0T} = \frac{\partial (MF)}{\partial Q_{0T}} \tag{12}$$

$$\frac{u_{Q_{0T}}}{Q_{0T}} = \sqrt{\left(\frac{u_T}{Q_T}\right)^2 + \left(\frac{u_{PT}}{P_T}\right)^2 + \left(\frac{u_{TT}}{T_T}\right)^2} \tag{13}$$

$$U = t_{student} . u \tag{14}$$

2.2.4 Flow measurement (Q_{flow}) with turbine

$$Q_{flow} = MF . Q_{0T} \tag{15}$$

2.2.5 Uncertainty of flow measurement (U_{flow}) with the turbine. Approximate method.

The uncertainty of flow measurement (U_{flow}) with the turbine can be estimated using Eq. (15). Because of the fact that *MF* and Q_{0T} may not be statistically independent, there may exist a correlation between the two variables, not considered in this paper. An approximate solution is given by Eq. (16), neglecting the resolution of Q_{0T}.

$$\frac{U_{flow}}{Q_{flow}} = \frac{U}{MF} \tag{16}$$

2.2.6 Uncertainty of flow measurement (U_{flow}) with the turbine. Conventional method

The conventional procedure for estimating the uncertainty of measurement with the turbine starts with Eq. (15), where MF is only a function of Q_{0T} according to Eq. (7). The uncertainty (U_{flow}) of flow measurement (Q_{flow}), according to (Orlando, 2009), can be written as :

$$u_{flow} = \sqrt{u_{QM}^2 + u_{fit}^2 + (c_{0T}.u_{Q_{0T}})^2} \tag{17}$$

$$c_{0T} = \frac{\partial Q_{flow}}{\partial Q_{0T}} = MF + Q_{0T} \cdot \frac{\partial MF}{\partial Q_{0T}} \tag{18}$$

$$u_{fit} = \sqrt{\frac{1}{N-1}.\sum_{i=1}^{N}(Q_{0m,i} - Q_{flow,i})^2} \tag{19}$$

where $Q_{flow,i}$ is calculated with Eq. (15), using $Q_{0T,i}$., $Q_{0M,i}$ is the indicated volume by the master turbine at reference conditions, u_{QM} (standard uncertainty) is obtained from the uncertainty certificate of the master turbine, and $u_{Q_{0T}}$ from Eq. (13).

3. EXPERIMENTAL METHODS

3.1 Calibration Facility

The calibration facility used in this research, TRANSCONTROL, is being accredited to the Brazilian Calibration Network (RBC) and is shown in Fig. 1.Temperature and pressure transmitters, together with a turbine meter for volume measurement, supply calibration information through a data acquisition system with a RS232 interface and a dedicated software for processing the data.

The facility has 2”, 3”, 6” and 12” diameter turbines to be used as master meters. Temperature transmitters are placed in each line downstream of the respective turbine meters, which have pressure taps for pressure measurement. The master turbine and the turbine under calibration (test turbine) are placed in different lines.

Platinum resistance thermometers (Pt100) are used for temperature measurement with uncertainty of ± 0,5 °C (k=2). A better accuracy can be achieved if they are calibrated. Piezoelectric transmitters are used to measure pressure with uncertainty of ± 0,3 kPa (k=2) in the 0 –7 kPa range. Master turbines were used to measure volume with a maximum uncertainty of ± 0,33 % (k=2).

Figure 2 shows the connection between the different components of the measuring and processing system used for calibration purpose in the facility.

All volume, temperature and pressure data, read by the data acquisition system, are IEEE 754 (32 bits) formatted and used as input to the software for calculating the corrected volumes to the reference conditions and thus the volume deviation between master and test turbines.

Figure 1. Overview of the turbine calibration facility.

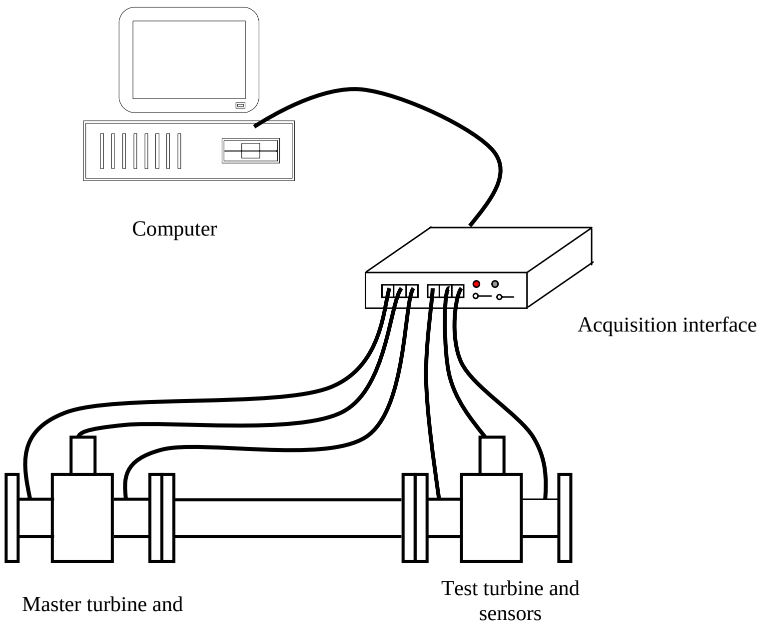

Figure 2. Schematics of the measuring and processing system of the turbine calibration facility.

3.2 Calibration procedure

The calibration procedure adopted by the calibration facility follows the methodology used for turbine type approval, (NBR ISO 9951/ABNT, 2002) and (Decree #114, 1997). The turbine test must be calibrated at least in 6 flow rate values between the minimum flow rate (Q_{min}) and the maximum flow rate (Q_{max}) : Q_{min} , 0,1 Q_{max} , 0,25 Q_{max} , 0,4 Q_{max} , 0,7, Q_{max} and Q_{max} .From the measured air temperature and pressure for both master and test turbine, the measured volumes are corrected to reference conditions, 20 °C and 101325 Pa.

For initial verification purpose, three (3) measurements must be made for each flow rate, to check the repeatability of results. The maximum difference between any two (2) out of three (3) measurements, made for each flow rate larger than the critical one, must be smaller than ± 1 % with respect to the master turbine volume, The average value is representative of the flow rate and the test turbine is considered to be approved if this condition is met.

For calibration purpose, a meter factor is defined as the ratio between the corrected master turbine volume and the corrected test turbine volume. Up to a third degree polynomial is used to fit the meter factor (MF) as a function of the indicated flow rate by the test turbine in the 0 – 800 m³/h range, by the least square method.

Another matter of concern is the proven volume for calibrating the turbine. Several volumes were used during the calibration and chosen the minimum one to minimize the meter factor (MF) uncertainty. For each flow rate, 10 calibrations were run to determine the repeatability. Table 1 specifies for each runs made the proven volume and the flow rate. A 6" diameter pipeline was used for the experiments.

Table 1. Proven volume and flow rate

Proven Volume (m³)	Flow rates (m³/h)
10	90, 180, 270, 360, 450, 540, 630, 720
20	90, 360, 450, 630
30	90, 360, 450, 630
40	90, 225, 270, 360, 450, 540, 630

4. RESULTS

As a first step towards the minimization of the calibration uncertainty, a study was conducted to determine the influence of the proven volume on the calibration, as indicated by the meter factor. Figure 3 shows that for low flow rates a 10 m³ volume can be used and causes a small influence on the calibration. However, when the flow rate increases, the error in the meter factor can be high, much more than what is allowed for the estimated uncertainty for volume measurement by the turbine. Figure 3 shows that if a minimum of 20 m³ volume is selected the calibration is not influenced by the proven volume, that is, the meter factor does not depend on the proven volume. Also, it can be seen that the meter factor is not constant with the flow rate and a curve fit is required for interpolation purposes, if a smaller uncertainty is desired.

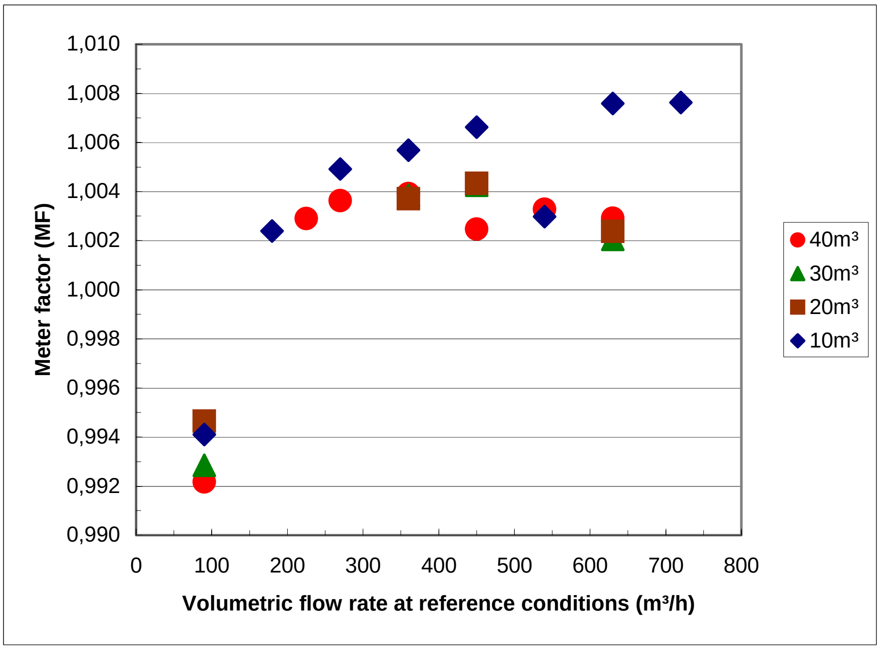

Figure 3 . Influence of the proven volume on the calibration, as indicated by the meter factor.

Another way of determining the minimum proven volume is by calculating the meter factor standard deviation. About 10 runs were made for each flow rate for its calculation. Figure 4 shows that when the proven volume is small (10 m³) the repeatability, as indicated by the meter factor standard deviation, is worse. For a minimum of 20 m³ volume, the repeatability is approximately the same.

It was decided to use a 40 m³ proven volume in the experiments for minimizing the standard deviation.

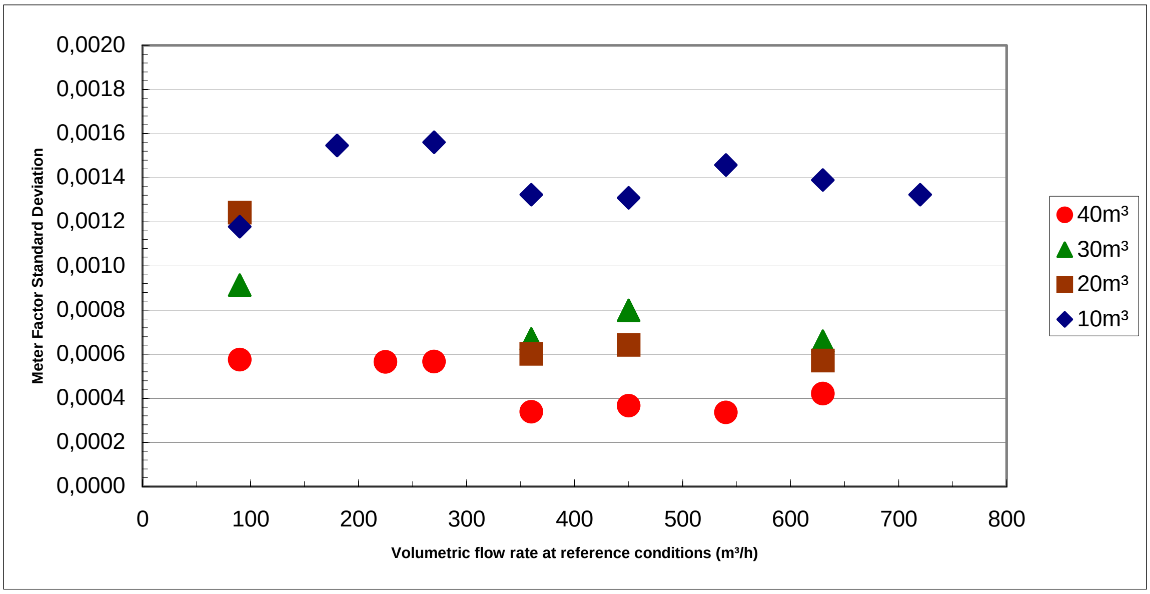

Figure 4. Influence of the proven volume on the calibration repeatability, as indicated by the standard deviation.

About 10 runs were made for each of the seven (7) tested volumetric flow rates to check the repeatability. All values were included in the least square fit (66 data points) so that the spread of each measured volume can be taken into account. Table 2 shows the standard deviation of the fitting for both meter factor and volumetric flow rate at reference conditions as a function of the polynomial degree. It can be seen that the third degree polynomial fits the data points better, as indicated by the lowest calculated deviation.

Table 2. Standard deviation of the least square fit.

PARAMETER	POLYNOMIAL DEGREE		
	3	2	1
Meter Factor	0,00085	0,00164	0,00290
Volumetric flow rate at ref. conditions (m^3/h)	0,283	0,567	0,751

Figure 5 shows the third degree polynomial fit to the data points. It can be seen that, for small flow rates, the spread is larger and the meter factor is smaller. A criterium for choosing the operating range of the turbine would be the specification of the acceptable meter factor range and spread of the measured volume, which is related to the uncertainty of measurement.

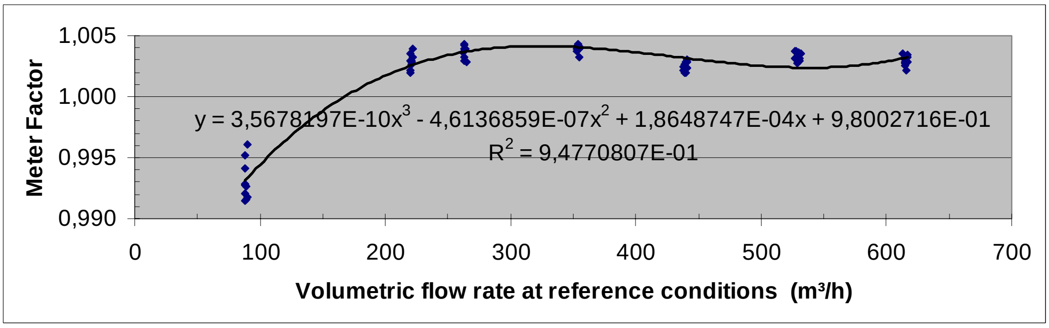

Figure 5. Third degree polynomial least square fit to data points.

Figures 6 and 7 show the second and first degree polynomial least square fit to data points. The goodness of the fit can be analyzed by the correlation coefficient as indicated in the graphs. The third degree polynomial is the best fit. The curve goes through most of the data points and will be therefore used.

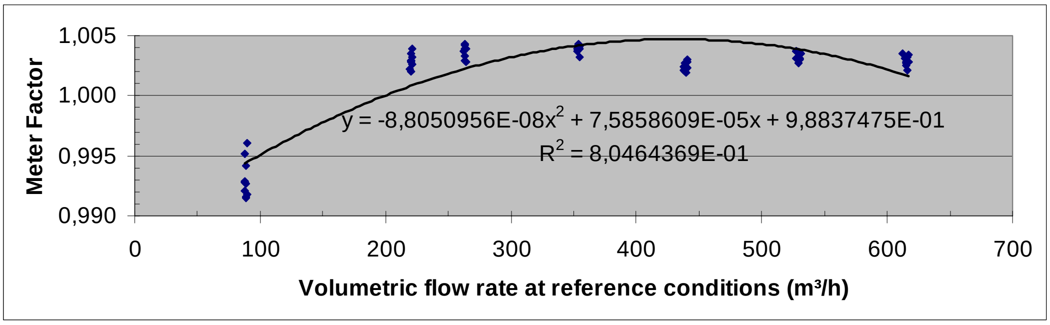

Figure 6. Second degree polynomial least square fit to data points.

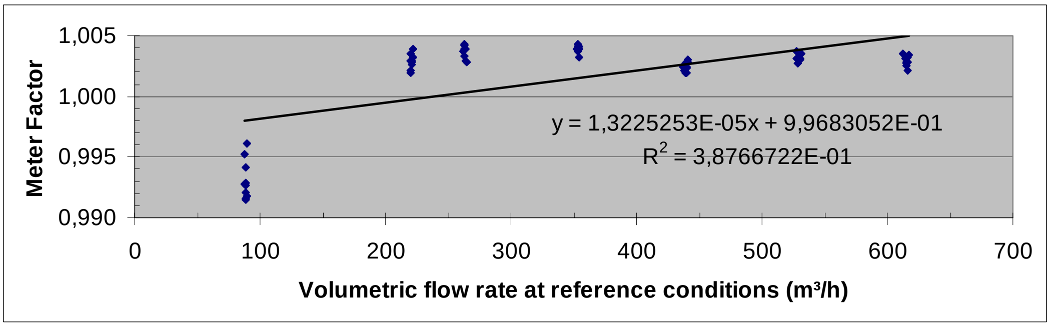

Figure 7. First degree polynomial least square fit to data points.

The next step in this methodology is to estimate the uncertainty of measurement of the volumetric flow rate by the turbine. Two methods were used. The first one, an approximate method, uses the meter factor and is more convenient. The second one, the conventional method, calculates the uncertainty directly from volumetric flow rate values.

A third degree polynomial least square fit to the data points was used to analyze the contribution of each parameter to the uncertainty of measurement of the volumetric flow rate by the turbine. Tables 3 and 4 show that the most important contribution is the conversion of the measured flow rate to reference conditions, due to pressure and temperature. Therefore, the uncertainty of flow rate measurement can be reduced if the temperature and pressure measurement can be made more accurately.

Table 3. Contribution to uncertainty of volumetric flow rate measurement. Meter Factor.

Q_{0T}	u_{MF}	u_{fit}	$c_{0T}.u_{0T}$	u	U	U/MF
m³/h						%
87,9	0,00290	0,00085	0,00002	0,0030	0,0062	0,62
221,2	0,00293	0,00085	0,00001	0,0031	0,0062	0,62
264,2	0,00293	0,00085	0,00001	0,0031	0,0062	0,62
355,0	0,00293	0,00085	0,00000	0,0031	0,0062	0,62
441,0	0,00293	0,00085	-0,00001	0,0030	0,0062	0,62
530,3	0,00293	0,00085	0,00000	0,0031	0,0062	0,62
617,5	0,00293	0,00085	0,00003	0,0031	0,0062	0,62

Table 4. Contribution to uncertainty of volumetric flow rate measurement. Volumetric flow rate at reference conditions.

Q_{0T}	u_{0M}	u_{fit}	$c_{0T}.u_{0T}$	u	U	U/Q_{0T}
m³/h	m³/h	m³/h	m³/h	m³/h	m³/h	%
87,9	0,145	0,283	0,15	0,35	0,72	0,81
221,2	0,367	0,283	0,38	0,60	1,23	0,55
264,2	0,437	0,283	0,45	0,69	1,41	0,53
355,0	0,587	0,283	0,60	0,89	1,82	0,51
441,0	0,728	0,283	0,75	1,08	2,21	0,50
530,3	0,873	0,283	0,90	1,29	2,63	0,50
617,5	1,017	0,283	1,06	1,50	3,07	0,50

A comparison between the results obtained by two methods, Tab. 3 and 4, shows that the method of calculating the uncertainty of measurement of volumetric flow rate at reference conditions by the meter factor slightly overestimates it at high flows and underestimates it at low flows, with respect to directly calculating it by the conventional method. The difference between the two methods gets small when the meter value variation is small, which seems to be the most adequate situation for using the meter factor method. The conventional method is able to estimate the uncertainty as a function of the flow rate. The meter factor method produces a reasonably constant value for the uncertainty, which lays between the upper and lower limits of the other method. The trend for both methods is an asymptotically constant value for high flow rates. Thus, the operating range of the turbine can be defined in terms of the region where the uncertainty varies to within a narrow band.

Finally, the influence of the curve fit over the uncertainty of measurement was studied, by varying the degree of the least square fit polynomial, as shown in Fig. 8, 9 and 10. It can be concluded that before estimating the uncertainty, a careful study on the curve fit must be made, for minimization of the uncertainty of measurement. The influence is larger when the meter factor variation is higher, which happens low flow rates.

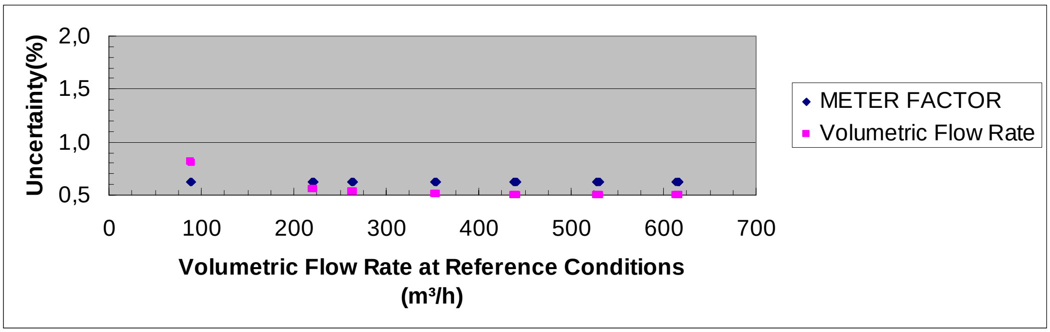

Figure 8. Uncertainty of volumetric flow rate measurement. Third degree polynomial least square fit.

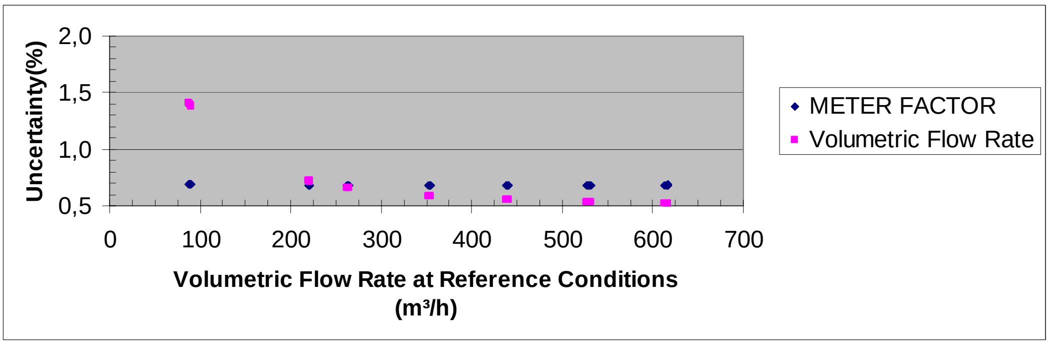

Figure 9. Uncertainty of volumetric flow rate measurement. Second degree polynomial least square fit.

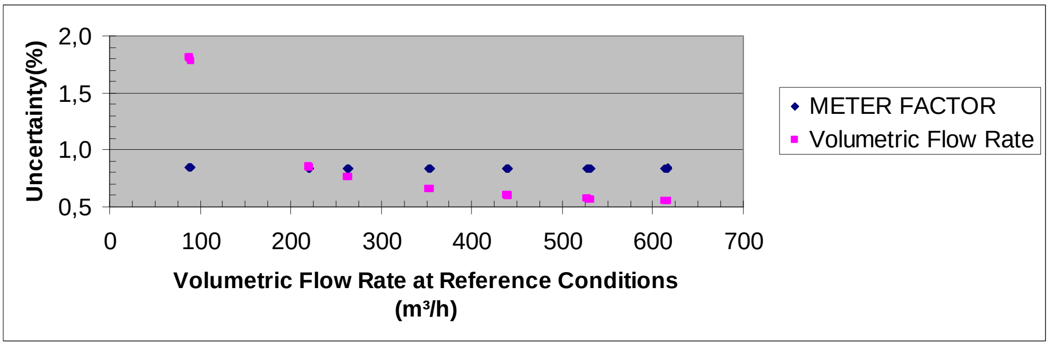

Figure 10. Uncertainty of volumetric flow rate measurement. First degree polynomial least square fit.

5. CONCLUSIONS

A procedure has been developed in this paper for calibrating a turbine for flow rate measurement, estimating its uncertainty and analyzing the test conditions for its optimization.

First of all, the measured flow rates by the master and test turbines are corrected to reference conditions of 20° and 101,325 kPa. Then, a meter factor is calculated. In order to smooth out the fluctuations, the meter factor was calculated as the ratio between the volumes of air through the master and test meters over a given period of time, as indicated by the proven volume and volumetric flow rate, directly indicated by the meters by counting pulses. A minimum proven volume of air was chosen so that its influence on the uncertainty of measurement is small.

For each set volumetric flow rate, several runs were made to check the repeatability of results. All those values were included in a polynomial least square fit for the meter factor as a function of the volumetric flow rate at reference conditions to include the spread of flow rate measurement by the meters. When in operation, the corrected volumetric flow rate to reference conditions, as measured by the test turbine, must be multiplied by the meter factor, resulting in the best estimate of the volumetric flow rate at reference conditions. The least square fit is considered as an interpolating scheme for non calibrated points. The polynomial degree was chosen to minimize the standard deviation of the curve fit for the measured points.

The uncertainty of measurement was estimated by a conventional method that fits a curve directly to the measured volumetric flow rate values. A second method, a more convenient one, calculates the uncertainty from the meter factor relationships. A comparison of the results shows that the most important contribution to the volumetric flow rate measurement is the conversion to reference conditions. Thus, if smaller values are to be obtained, temperature and pressure must be more accurately measured.

It was concluded that the conventional method is able to estimate uncertainty as a function of the flow rate. The meter factor method estimates a reasonably constant value along the flow rate range, laying between the upper and lower limits of the first one. The difference between the two methods gets smaller when the variation of the meter factor along the range is smaller, which seems to be the most adequate situation for using the meter factor method. Anyway, both methods produce an asymptotically constant value for the uncertainty at higher flow rates. As a criterium for choosing the operating range of the turbine, a flow rate range may be specified so that the uncertainty band be to within desired limits.

Finally, it was shown that a careful study of the curve fit must be made because it has a large effect on the uncertainty of measurement.

6. ACKNOWLEDGEMENTS

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