Time dependent performance of turbine gas meters

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ABSTRACT

Gastransport Services in the Netherlands, uses turbine gas meters to measure the gas flow to local gas distribution companies, large industrial customers and power plants GTS operates approximately 1100 city gate stations, at a delivery pressure of usually 8 bar.

In the Netherlands, the procedures for determining the operational performance of the turbine meters are agreed upon between Gastransport Services and its customers. As a result of this agreement, Gastransport Services inspects the total population of turbine meters by means of the well-known *variables-acceptance-sampling*. Each year, 60 turbine meters are selected randomly from the total population. Subsequently, the selected turbine meters are calibrated traceable to international standards by Netherlands Measurment Institute (NMi). The information from these recalibrations is used to study the stability of the turbine meters.

Because, through the years a lot of information has been gathered on the turbine meters performance, the presence of statistically significant relationships (correlation) between the performance in time of the meters on the one hand and properties like the construction year, the pressure class, the size, the maximum allowable flow rate and/or the recalibration period of the meter on the other hand, can be investigated. In this presentation, *analysis-of-variance* and the *quadrant-correlation-test* are used to test for the presence of such correlations.

The aforementioned five properties were analysed for the presence of correlation at two different calibration pressures and with different definitions of drift to express the performance in time of gas turbine meters. For a specific calibration pressure and a specific type of drift, the performance in time dependents on the recalibration period and the size of the turbine meter.

Furthermore, the correlation analysis, showed that a turbine gas meter seems to reach a steady state in time, expressed in terms of shift of the weighted mean error.

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KEYWORDS: Time dependent performance, turbine meters, drift, shift of the weighted mean error, analysis-of-variance, quadrant-correlation-test, least significant difference, correlation analysis

1. INTRODUCTION

Turbine meters are commonly used in gas flow metering. If properly calibrated, operated and maintained, the turbine meter can be considered as one of the most accurate measuring technique available at this moment.

As a part of N.V. Nederlandse Gasunie, Gastransport Services operates the main gas transmission grid in the Netherlands and uses for the metering of the natural gas delivered to its customers in the Netherlands already approximately 2500 turbine meters ranging in size from D=4″ to 24″. Before a new turbine meter is taken into operation, it is not only calibrated with air at atmospheric conditions but also at operational conditions with natural gas. This calibration procedure guarantees the most accurate measurements during normal operation.

In the Netherlands, the procedures for determining the operational accuracy of the turbine meters are agreed upon between Gastransport Services and its customers. As a result of this agreement, Gastransport Services inspects the total population of turbine meters by means of the well-known *variables-acceptance-sampling*. Each year, 60 turbine meters are randomly selected from the total population. Subsequently, the selected turbine meters are calibrated against traceable international measurement standards by the Dutch institute for metrology and technology (NMi). The information from these recalibrations is used to study the stability of the turbine meters.

Because a lot of information has been gathered on the turbine meters during the years, the possible presence of statistically significant relationships between the time behaviour of turbine meters on one hand and properties like the construction year, the pressure class, the size, the maximum allowable flow rate (Q_{max}) and/or the recalibration period of the meter on the other hand can be tested for. In this paper the correlation techniques used to test for the presence of such correlations will be described as well as some results.

2. TIME DEPENDENT PERFORMANCE

The selection of 60 turbine meters from the total population of about 2500 is based on the sample plan for *variables-acceptance-sampling*. Each selected turbine meter is recalibrated at the same conditions as used during the initial calibration. Calibration is carried out at the standardised test flow rates Q_i= 0.05, 0.10, 0.25, 0.40, 0.70 and 1.0 Q_{max}. Using the initial high pressure calibration data, the shift S_i of the error E_i at each flow rate Q_i is defined by:

$$S_i = E_i(repeat) - E_i(initial^*) \qquad (1)$$

(*): Initial refers to the calibration before last in case of multiple recalibrations of the meter

The shift of the weighted mean error per unit time, is a convenient parameter to describe the time dependent meter performance. This so called *drift* is defined by:

$$drift \quad = \quad \left[\frac{\sum_i W_i \cdot S_i}{\sum_i W_i} \right] \Bigg/ \Delta t \qquad (2)$$

In this definition, Δt is the time gap between the last and last but one calibration, commonly expressed in years.

The shift, S_i, is weighted per flow rate, Q_i. Two types of weighing are used to calculate the drift (hereafter referred to as drift 1 and drift 2). The first type of weighing, type 1 drift is based on the standard weighing used for turbine meters. Type 2 drift is a dedicated weighing method applied for turbine meters which are rarely operated at maximum allowable flow rate (Q_{max}). The weighing factors for the two drift types at different flow rates are given in the table below.

Type	Flow rate percentage of Q_{max} :	5%	10%	25%	40%	50%	70%	100%
Drift 1	Weighing factor (W_i) :	0.05	0.10	0.25	0.40		0.70	0.40
Drift 2	Weighing factor (W_i) :	0.1	0.25	0.4	0.7	0.4		

Table 1. Weighing factors respectively to flow rates for two types of weighing.

Throughout this article the *drift* is used as a representative measure of the performance in time of turbine meters.

3. CORRELATION ANALYSIS

3.1. Discrete and continuous variables

The presence of correlation is analysed on a property basis. The five properties taken into consideration in this study can be divided into two classes. The properties *construction year*, *pressure class*, *size* and *maximum allowable flow rate (Q_{max})* are considered to be discrete variables. The property *recalibration period* is considered to be a continuous variable.

Each discrete property is subdivided in a number of individual groups. In most cases these subdivisions are based on the physical properties of a turbine meter. In table 2 for each discrete property, an overview is given of the classification used. The limits, on which the group ranges are based, are given per group.

Property	# groups (k)	Group 1	Group 2	Group 3	Group 4	Group 5
Construction year	5	- 1972	1973 – 1974[*]	1975 - 1984	1985 – 1994	1995 - 2002
Pressure class	3	ANSI 150	ANSI 300	ANSI 600		
Size (mm)	3	0 – 150	200 – 250	300 – 500		
Q_{max} m^3/h	2	0 – 650	> 650			

(*): transition type
Table 2. Classification for discrete properties

The presence of correlation between the performance in time of a turbine meter and each discrete property is studied by using a *ANalysis-Of-VAriance* (ANOVA) technique. For each discrete property, the individual groups are treated as independent variables. For each individual group, the performance in time of the turbine meter, previously defined as drift of type 1 or type 2, is used as dependent variable. When the *analysis-of-variance* indicates correlations, a *Least-Significant-Difference* test is carried out.

The presence of correlation between the performance in time of a turbine meter and the continuous property *recalibration period* is analysed with the well-known *Quadrant-Correlation-Test*.

3.2. *Analysis-of-variance (ANOVA)*

In an *ANOVA* the variation in the response measurements is partitioned into components that correspond to different sources of variation. The goal in this procedure is to split the total variation in the data into a portion due to random error and portions due to changes in the values of the independent variable(s). *ANOVA* makes use of sums of squares, SS_{tot}, which is defined as the squared distance between each data point and the overall mean, summed for all data points. The sum of squared deviations presents variation in a form, which can be partitioned into different components that sum to give the total variation (e.g. the component of variation between groups and the component of variation within groups).

The sum of squares within groups, SS_{within}, is defined as the squared distance between each data point in a group and it's the group mean.

The sum of squares between groups, $SS_{between}$, is defined as the squared distance between the (group) means and the overall mean, weighted by the number of elements in the respective samples (groups) (n_i). The following relationship exists between SS_{total}, SS_{within} and $SS_{between}$:

$$SS_{total} = SS_{within} + SS_{between} \qquad (3)$$

Given *k* groups of sizes n_i, *i=1, .., k,* the combined size *n*:

$$n = \sum_{i=1}^{k} n_i \qquad (4)$$

The sample values x_{ij} have two indices; x_{ij} is the *j*th value in the *i*th group. The group means, $\overline{x}_{i.}$, are calculated as follows:

$$\overline{x}_{i.} = \frac{1}{n_i} \sum_{j=1}^{n_i} x_{ij} \qquad (5)$$

and the overall mean, $\overline{x}$, is calculated as:

$$\overline{x} = \frac{1}{n} \sum_{i=1}^{k} \sum_{j=1}^{n_i} n_i \cdot x_{ij} = \frac{1}{n} \sum_{i=1}^{k} n_i \overline{x}_{i.} \qquad (6)$$

Partition of the total sum of squares gives:

$$\sum_{i,j} (x_{ij} - \overline{x})^2 = \sum_{i,j} (x_{ij} - \overline{x}_{i.})^2 + \sum_{i} (\overline{x}_{i.} - \overline{x})^2 \qquad (7)$$

with the corresponding degrees of freedom:

$$n - 1 = \sum_{i=1}^{k} (n_i - 1) + k - 1 \qquad (8)$$

To estimate the variance in an *ANOVA*, the sums of squares needs to be divided by the respective degrees of freedom, for example $SS_{total}/(n-1)$. In *ANOVA*, these terms are called the mean sum of squares (*MS*).

If all groups originate from the same population, the mean sum squares between groups, $MS_{between}$, and the mean sum squares within groups, MS_{within}, should have the same order of magnitude.

$$s^2_{between} = MS_{between} = \frac{1}{k-1} \sum_i n_i (\bar{x}_{i.} - \bar{x})^2 \qquad (9)$$

$$s^2_{within} = MS_{within} = \frac{1}{n-k} \sum_{i,j} (x_{ij} - \bar{x}_{i.})^2 \qquad (10)$$

If this is not the case, i.e. if the quotient of $MS_{between}/MS_{within}$ is larger than the critical value of the *F*-distribution defined by $\boldsymbol{n_1}=k-1$, $\boldsymbol{n_2}=n-k$, and $\boldsymbol{a}$, at least two groups have different means μ_i. In this case, the alternative hypothesis that μ_i unequals μ_j for some (*i,j*) is accepted and correlation between the groups is expected [3].

3.3. *Quadrant-Correlation-Test (QCT)*

The QCT checks whether two continuous variables x and y, known through data, are independent. In this statistical test, pairs of values (x_i, y_i) are plotted individually in a coordinate system. The data pairs are partitioned into four quadrants by the two medians $\tilde{x}$ and $\tilde{y}$. If the number of data pairs is odd, the horizontal median line passes through one point, which is subsequently ignored. A significant relationship between attributes is ascertained as soon as the number of points in a single quadrant does not lie within the statistical bounds [1].

3.4. *Least-Significant-Difference (LSD)*

In those cases, in which the *ANOVA* shows at least two groups with different means, a LSD test was carried out. A *LSD* test gives detailed insight in the groups that differ significantly and groups that do not differ significantly from one another. This test reveals several significant different populations enclosing one or more specific group means Thus groups enclosed in one population don't differ significant from one another. The *LSD* test employs the t statistic:

$$t_0 = \frac{\bar{x}_{i.} - \bar{x}_{j.}}{\sqrt{s^2_{within}(\frac{1}{n_i} + \frac{1}{n_j})}} \qquad (11)$$

Assuming a two-sided alternative, the pair of means μ_i and μ_j would be declared significantly different if

$$\left| \overline{x}_{i.} - \overline{x}_{j.} \right| > t_{a/2,n-k} \sqrt{s^2_{within}(\frac{1}{n_i} + \frac{1}{n_j})} \qquad (12)$$

The quantity

$$LSD = t_{a/2,n-k} \sqrt{s^2_{within}(\frac{1}{n_i} + \frac{1}{n_j})} \qquad (13)$$

is called the least significant difference. All observed differences between each pair of averages to the corresponding LSD are compared. If $\left| \overline{x}_{i.} - \overline{x}_{j.} \right|$ > LSD it can be concluded that the population means μ_i and μ_j differ.

4. DATA SETS

The actual correlation study is based on two datasets. The first dataset consists of 168 values of drift. These values are based on calibrations at 8 bar with natural gas. The second dataset consists of based on 27 values of drift. These values are based on calibrations with air at 1 bar. On both datasets, outlier tests were performed before the actual correlation work was started.

For the correlation analysis of the discrete properties the number of data points (drift values) per group are given in table 3.

Property	Calibration pressure	Drift estimations per group (n_i)				
		Group 1	**Group 2**	**Group 3**	**Group 4**	**Group 5**
Construction year	1 bar	11	16			
	8 bar	1	4	54	103	2
Pressure class	1 bar	27				
	8 bar	159	8	1		
Size (mm)	1 bar	13	12	2		
	8 bar	80	79	9		
Max flow m^3(n)/h	1 bar	10	17			
	8 bar	52	116			

Table 3. Number of drift values per group used for the correlation analysis of the discrete properties

5. RESULTS AND DISCUSSION

5.1 Recalibration period

The QCT indicates a dependency between the recalibration period and type 2 drift at a calibration pressure of 8 bar. No indication was found for a correlation between the recalibration period and type 1 drift. In figure 1 type 1 drift and type 2 drift are plotted against the recalibration period.
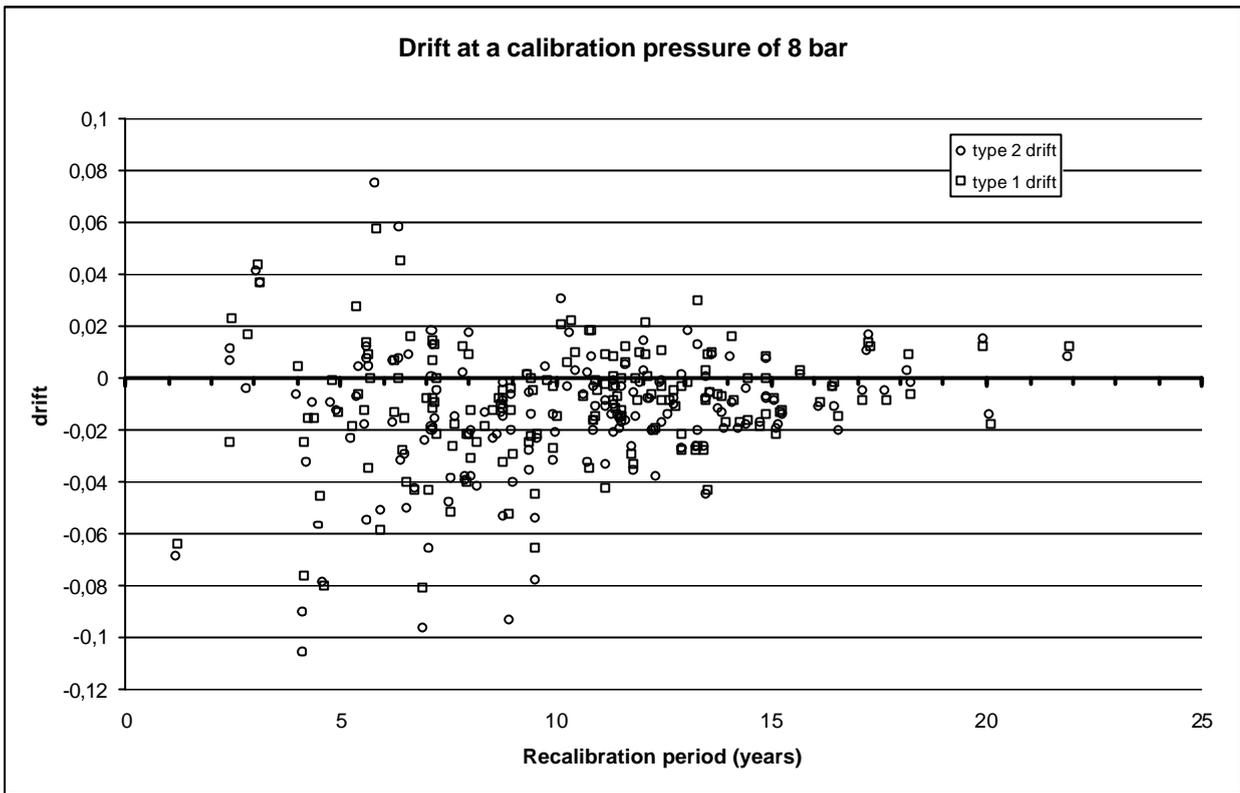
Figure 1.Type 1 drift and type 2 drift against the recalibration period at a calibration pressure of 8 bar

In figure 1 it can be seen that the drift tends to decrease for longer recalibration periods. In table 4 the mean value of type 1 and type 2 *drift* is given for several recalibration periods, clearly indicating the decrease of drift in time.

recalibration period	type 1 drift	type 2 drift
1 to 5 years	-0.016	-0.025
5 to 10 years	-0.014	-0.019
10 to 15 years	-0.005	-0.010
15 years and more	-0.003	-0.004

Table 4. Overview of mean values of type 1 and type 2 drift for several recalibration periods

From formula 2 it can be seen that decreasing drift with an increasing recalibration period, Δt , is only

possible if the term $\left[\dfrac{\sum\limits_{i} W_i \cdot S_i}{\sum\limits_{i} W_i} \right]$, the shift of the weighted mean error, remains constant. This means

that a turbine gas meter reaches a steady state in terms of a shift of weighted mean error.

For both type 1 drift and type 2 drift, the QCT indicates no correlation with the recalibration period for the calibrations carried out at a calibration pressure of 1 bar with air.

5.2. Discrete properties

The results of the correlation analysis based on ANOVA for the discrete properties are given in table 5. The presence of correlation for both calibration pressures and both drift types is indicated by a "+" sign. A "-" sign indicates absence of correlation. Furthermore calculated F-values (F_{calc}) and theoretical F-values (F_{tab}) resulting from the *ANOVA* analysis are given. In case of correlation F_{calc} is larger than F_{tab}.

Property	Calibration pressure	Presence of correlation for drift of type 1		Presence of correlation for drift of type 2	
		correlation	F_{calc} , F_{tab}	correlation	F_{calc} , F_{tab}

Construction year	1 bar	-	0.02 , 4.24	-	0.05 , 4.24
	8 bar	-	1.25 , 2.43	-	1.08 , 2.43
Pressure class	8 bar	-	1.79 , 3.05	-	0.29 , 3.05
Size (mm)	1 bar	-	1.10 , 3.40	-	0.32 , 3.40
	8 bar	+	8.33 , 3.05	+	4.54 , 3.05
Max flow m^3(n)/h	1 bar	-	0.01 , 4.24	-	0.03 , 4.24
	8 bar	-	1.12 , 3.90	-	0.17 , 3.90

Table 5. Overview of correlation analysis for the discrete properties.

The ANOVA analysis between property *size* and type 1 *drift* and type 2 *drift* at a calibration pressure of 8 bar indicates the presence of correlation. This correlation was further analysed with the LSD method to determine which of the three groups belong to the same population (see table 2).

For type 1 drift, the LSD method indicates two significant different populations. The first population encloses group 1 (0 – 150 millimetres) and group 3 (300 - 500 millimetres) whereas the second population only encloses group 2 (200 – 250 millimetres).

For type 2 drift, the LSD method indicates again two significant different populations. The first population encloses group 1 (0 – 150 millimetres) and, in contrast to type 1drift, group 2 (200 - 250 millimetres). In this case the second population is formed by group 3 (300 - 500 millimetres).

6. Conclusions

Five properties were analysed for the presence of correlation at two different calibration pressures and two types of weighing to express the performance in time of turbine gas meters. For a specific calibration pressure and a specific type of weighing, the performance in time is dependent on the recalibration period and the size of the turbine meter. From the analysis, it can be concluded that the recalibration period at a calibration pressure of 8 bar and type 2 drift is correlated. For both type 1 drift and type 2 drift, a correlation is found with the size of the turbine meter at a calibration pressure of 8 bar.

The correlation analysis carried out on the time interval between two successive calibrations (recalibration period) have showed that:
1. The drift decreases with increasing time intervals.
2. A turbine gas meter reaches a steady state in terms of a shift of weighted mean error.

Based on the results of the perfomance in time of turbine meters in this paper, it can be concluded that the procedure Gastransport Services uses tot inspect turbine gas meters is a suitable way to get grip on the total population of turbine meters Gastransport Services uses.

7. References

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