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Liquid hydrocarbons — Dynamic measurement — Statistical control of volumetric metering systems

Hydrocarbures liquides — Mesurage dynamique — Contrôle statistique des systèmes de mesurage volumétrique

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Contents

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Annexes

Foreword

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Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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Annexes A, B, C, D, E and F of this International Standard are for information only.

Liquid hydrocarbons — Dynamic measurement — Statistical control of volumetric metering systems

Section 1: General

1.1 Scope

In dynamic measuring systems the performance of meters for liquid hydrocarbons will vary with changes in flow conditions, viz. flowrate, viscosity, temperature, pressure, density of product, and with mechanical wear.

This International Standard has been prepared as a guide for establishing and monitoring the performance of such meters, using appropriate statistical control procedures for both central and on-line proving. These procedures may be applied to measurements made by any type of volumetric or mass metering system.

The procedures to be followed for collecting data, on which the control limits are based, are described. An alternative method for establishing the reliability of these data is described in ISO 7278-3.

Methods are described for calculating the warning and action control limits for the charts covering the selected performance characteristics, the application of these control charts to subsequent routine measurements, and their interpretation. Worked examples are given in the appropriate central and on-line proving sections.

1.2 Definitions

For the purposes of this International Standard, the following definitions apply.

1.2.1 proving; proof; calibration: Determination of the meter performance via the relationship between the volume of liquid actually passing through a meter and the reference volume of the pipe prover.

1.2.2 *K*-factor: Relationship between the number of pulses (N) generated by the meter during the proving run and the volume of liquid (V) displaced by the sphere or piston in the pipe prover between detectors.

Normally, $K = N/V$; it is recommended that this value be corrected by the pulse interpolation technique described in ISO 7278-3.

1.2.3 meter factor: Ratio of the actual volume passed through a meter, as derived from the pipe prover, to the volume indicated by the meter totalizer.

1.3 Symbols and units

1.3.1 General symbols

h_1	high liquid level in tank	metres
h_2	low liquid level in tank	metres
E_h	gauging error	millimetres
E_m	meter volumetric error	percent
E_t	temperature error	degrees Celsius
K	K-factor	pulses per unit volume
ΔK	change in K-factor	pulses per unit volume
MF	meter factor	dimensionless
MF_m	mean meter factor	dimensionless
MF_{max}	maximum meter factor in a set of measurements	dimensionless
MF_{min}	minimum meter factor in a set of measurements	dimensionless
N	number of pulses generated by meter during proving run	dimensionless
p	pressure at line conditions	kilopascals (1 bar = 100 kPa)
p_0	pressure at standard conditions (101,325 kPa)	kilopascals
t	temperature at line conditions	degrees Celsius
t_0	temperature at standard conditions (15 °C or 20 °C)	degrees Celsius
T_1	elapsed time	seconds
Q	volume rate of flow	cubic metres per hour
V_p	reference volume of pipe prover at standard conditions (15 °C or 20 °C and 101,325 kPa)	litres or cubic metres
v	kinematic viscosity of the fluid	millimetres squared per second [centistoke (cSt)]

1.3.2 Statistical symbols

X	true value of quantity
μ	mean value
σ	standard deviation
x	value of measurement
$\bar{x}$	mean of a set of measurements
n	number of repeated measurements
m	number of quantities
s	estimate of standard deviation
w	range of a set of measurements
$\bar{w}$	mean of a set of ranges
t	value of Student's t-distribution
r	estimate of repeatability
Φ	degrees of freedom

1.4 Central proving

With the method of central proving, the performance of a meter is established at a testing station by proving the meter over its entire operating range of flowrate, viscosity, temperature and oil density used in service.

Meter performance charts are then prepared from the proving data, and are used to establish the relationship between the meter factor and flowrate or flow and viscosity.

Any large deviation in meter performance on site can be detected by secondary control procedures, which monitor the output of two meters in series or in parallel. Long-term deviations in meter factors can be established by statistical control charts. The latter method can also be used in on-line proving.

1.5 On-line proving

With the method of on-line proving, the meter is proved under operating conditions with a portable or fixed installation pipe prover. Where significant changes in flowrate, viscosity, temperature or density occur, the meter can be reproved.

Any marked deviation or abnormal trend in meter factor can be monitored by use of statistical control charts.

By statistical analysis it is possible to establish whether the deviations are due to changes in flow conditions, random error or some other assignable cause.

Section 2: Statistical measurements

2.1 Principles of statistical measurement

2.1.1 Introduction

Measurements taken via central or on-line meter proving provide information on the random variability of the parameters of hydrocarbon flow through the meter (for example meter factor, flowrate, temperature, Reynolds number). Using this information, it is possible to assign a level of probability to a deviation observed in practice, and thereby differentiate between a normal or "allowable" deviation and one that has been caused by an external and systematic influence, such as meter component wear.

The true value of the meter characteristic in question, and its range of variability, can be represented diagrammatically on a control chart (see 2.2.5). This will indicate the deviation (warning limit) which should be taken as an early indication of malfunction, and the deviation (action limit) at which it is almost certain that meter failure has occurred. It is standard practice to assign a probability of 95 % to warning limits, and 99 % to action limits. This means, for example, that there is only a 1 % chance that a measurement falling outside the action limits did so as a result of normal variation when the process is under statistical control. Once a control chart is established, the measurements from subsequent meter provings can be entered periodically onto the control chart, from which it is possible to monitor trends in meter performance over a period of time.

In order to establish control through this means, reliable estimates should be obtained of the statistics to be used. The initial period in which data is collected, and against which the performance of the meter is to be monitored, is called the "learning period". This should be long enough to provide a reliable assessment of the true value of the meter characteristic in question.

Before considering the steps to be followed in the creation, use and maintenance of control charts, it is first necessary to understand the statistical treatment which is to be applied.

2.1.2 Distribution of measurements

The measurement of any physical quantity, be it direct (for example temperature by thermometer) or indirect (for example meter factor) is always subject to error. The error is sometimes systematic and assignable to a definite cause, for example a large change in temperature may result in a large change in meter factor. If that is not the case, however, data scatter can be regarded as random, and is thus amenable to statistical treatment.

Random errors often vary in magnitude with the quantity being measured (in which case they are expressed as percentages) or with some other external factor. The error in K-factor, for example, will change in magnitude according to the flowrate (see performance chart in figure 1). For this reason it is vital that operating conditions are controlled while measurements are being taken (see 2.2.2). In practice, the distribution of errors approximates a Gaussian (normal) distribution, and this is fully defined if its two parameters are known. The parameters in this case are mean value, represented by μ, and standard deviation, represented by σ. The Gaussian distribution is described in more detail in annex C.

Each of the parameters of a distribution of measurements is assumed to have a true value, and is represented algebraically by a Greek or capital Roman letter. Estimates of the parameters, or statistics, are represented algebraically by small Roman letters. When necessary these will be qualified algebraically by the use of brackets. For example the standard deviation estimate of a measurement x will be shown as $s(x)$ (see 2.1.4). The statistics which are of primary interest are mean, standard deviation, range of a set of measurements, and uncertainty.

2.1.3 Estimate of true quantity

Given a set of measurement x_i, for $i = 1$ to n, the estimate of the true quantity which is most likely to be correct is the mean $\bar{x}$ (termed "x bar") of the set of measurements, where

$$\bar{x} = \frac{1}{n} \ (x_1 + x_2 + ... + x_n) = \frac{1}{n} \sum_{i=1}^{n} x_i \qquad ...(2.1)$$

As n tends to infinity, so the estimate x will tend towards the true value μ, provided there are no systematic errors.

2.1.4 Estimate of standard deviation

The standard deviation $\sigma(x)$ is a measure of the random error of a single measurement x. The usual unbiased estimate of $\sigma(x)$ is $s(x)$, where:

$$s(x) = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2} = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} x_i^2 - \frac{n}{(n-1)} \bar{x}^2} \qquad ...(2.2)$$

Another estimate is given by:

$$s(x) = \frac{\bar{w}}{D(n)} \qquad ...(2.3)$$

where

$\bar{w}$ is the mean range difference between the maximum and minimum values of x, using a number of sets of n measurements;

$D(n)$ is a conversion factor (see annex A).

This estimate becomes less reliable as the number of ranges on which it was based becomes smaller, and should only be regarded as a rough check when based on a single range.

The standard deviation estimate of a mean, sometimes called standard error, is derived from this as:

$$s(\bar{x}) = s(x)/\sqrt{n} \qquad ...(2.4)$$

It is evident that as the number n of measurements is increased, so the standard error is decreased, leading to greater confidence in the estimate $\bar{x}$ of the true quantity.

2.1.5 Estimate of the uncertainty

The reliability of an estimate can be expressed as an *uncertainty interval* in which the true value should be expected to fall with a specified level of confidence or probability. In statistical terminology this is called a confidence interval. The uncertainty interval which contains an estimate x is $x \pm \mathrm{u}(x)$, where $\mathrm{u}(x)$ is called the *uncertainty*, $x - \mathrm{u}(x)$ and $x + \mathrm{u}(x)$ are called the *uncertainty limits*, and the difference $2\mathrm{u}(x)$ between these limits is called the *range of uncertainty*. Normally the probability levels are 95 % and 99 %.

A true quantity estimate of $\bar{x}$, the mean of n measurements, could then be stated as:

True quantity $= \bar{x} \pm \mathrm{u}(\bar{x})$, n measurements, 95 % probability;

when $n = 1$, $\bar{x}$ becomes the single measurement x.

If the standard deviation σ is known from long experience, then the uncertainty is also known. That referring to 95 % probability is given by:

$$\mathrm{u}(\bar{x}) = 1{,}96\sigma(\bar{x}) = 1{,}96\sigma(x)/\sqrt{n} \qquad ...(2.5)$$

As before, $\bar{x}$ becomes the single measurement x when $n = 1$. The value 1,96 is the value of the standard normal deviate for a two-sided probability of 95 % (see annex C).

If, however, the standard deviation of individual measurements has been estimated as $s(x)$, based on Φ degrees of freedom, then the uncertainty should be estimated as:

$$u(\bar{x}) = t_{95,\Phi} s(\bar{x}) = t_{95,\Phi} s(x)/\sqrt{n} \qquad \ldots (2.6)$$

Once again, when $n = 1$, $\bar{x}$ becomes the single measurement x.

Here $t_{95,\Phi}$ is the value of the t-distribution for a two-sided probability of 95 %, corresponding to a standard deviation estimate based on Φ degrees of freedom (see annex B). In this context, degrees of freedom should be regarded as the number of independent measurements from which the standard deviation was estimated. Given n measurements, therefore, s would be based on $\Phi = (n - 1)$ degrees of freedom, since one degree of freedom was already accounted for in estimating the mean.

The t-distribution is a function of the degrees of freedom, and the t-value for a given probability will decrease in magnitude as Φ increases. As Φ tends towards infinity, so the t-distribution tends towards a Gaussian distribution. Values of 2 and 3 are sometimes used as approximations of the t-values corresponding to 95 % and 99 % probability respectively. These values are appropriate for estimates based on 10 to 20 measurements.

2.1.6 Estimate of repeatability

Repeatability is the term used for uncertainty which relates not to individual measurements or measurement means as in 2.1.5, but to the *difference* between two individual measurements. Since the standard deviation of the difference between two measurements x_1 and x_2 (see 2.1.8) is:

$$\sigma(x_1 - x_2) = \sqrt{2}\ \sigma(x_1) = \sqrt{2}\ \sigma(x_2) \qquad \ldots (2.7)$$

then the repeatability estimate r is given by:

$$r = \sqrt{2}\ u(x) \qquad \ldots (2.8)$$

In this case $u(x)$ refers to individual measurements x_i rather than the mean $\bar{x}$, and equations (2.5) and (2.6) would become:

$$U(x) = 1{,}96\sigma(x) \qquad \ldots (2.9)$$

and

$$u(x) = t_{95,\Phi} s(x) \qquad \ldots (2.10)$$

Note that a repeatability value, to be used in practice, should be derived from an independent set of measurements which excludes the pair of values in question. The standard deviation estimate should be based on at least 20 and preferably 30 or more degrees of freedom.

2.1.7 Estimate of maximum range

It is possible to extend the concept of repeatability (the uncertainty for the difference between two measurements) by considering the distribution of a range of three or more measurements. For this it is necessary to refer to the limiting values $E_1(n)$ or $E_2(n, \Phi)$ of a range of measurements with unit standard deviation corresponding to a chosen probability level (see annex A).

The upper limit of the range of n measurements, knowing the standard deviation $\sigma(x)$, is given by:

$$W = \sigma(x)\ E_1(n) \qquad \ldots (2.11)$$

Where the standard deviation is estimated as $s(x)$ (see 2.1.4) based on Φ degrees of freedom, from an independent exercise excluding the measurements in question, the limit is estimated to be:

$$w = s(x)\ E_2(n, \Phi) \qquad \ldots (2.12)$$

In either case, the limit calculated corresponds to the maximum range (n measurements) to be expected in practice with the given probability. The limit corresponding to 95 % probability may be used as a test to establish statistical control (see 2.2.2). A rogue value can also be identified in this way (see 2.2.3), but should be confirmed by the use of one of the outlier tests given in annex D. As with repeatability, an estimate of maximum range to be used in practice should be based on at least 20 and preferably 30 or more degrees of freedom, and should exclude the measurements in question.

2.1.8 Combination of errors

Consider an indirect measurement y which is calculated from, say, m intermediate measurements x_1, x_2 ... x_m according to the function:

$$y = F(x_1,\ x_2 \ldots x_m) \qquad \ldots (2.13)$$

If the m intermediate measurements are algebraically independent, that is, no one can be calculated from the others, then the statistics of the indirect measurement may be derived as shown below.

2.1.8.1 The estimate $\bar{y}$ of the true value (see 2.1.3) can be calculated by substitution of the appropriate means into equation (2.13), that is:

$$\bar{y} \simeq F(\bar{x}_1,\ \bar{x}_2 \ldots \bar{x}_m) \qquad \ldots (2.14)$$

This approximation applies to functions F which are approximately linear.

2.1.8.2 The estimate $s(y)$ of the standard deviation of y (see 2.1.4) is given by:

$$s^2(y) = \left[\frac{\partial F}{\partial x_1} s(x_1)\right]^2 + \left[\frac{\partial F}{\partial x_2} s(x_2)\right]^2 + \ldots + \left[\frac{\partial F}{\partial x_m} s(x_m)\right]^2 \qquad \ldots (2.15)$$

where the sensitivity coefficients $\partial F/\partial x_i$ are evaluated at the known or mean values of x_i.

Note that the standard deviation estimates used in this expression could be in terms of either individual measurements [equation (2.2)] or mean values [equation (2.4)]. Furthermore, the expression is valid if one or more of the standard deviation values is known as $\sigma(x_i)$, rather than estimated as $s(x_i)$.

2.1.8.3 The estimate $u(y)$ of the uncertainty of y (see 2.1.5) is similar in form to equation (2.13), that is:

$$u^2(y) = \left[\frac{\partial F}{\partial x_1} u(x_1)\right]^2 + \left[\frac{\partial F}{\partial x_2} u(x_2)\right]^2 + \ldots + \left[\frac{\partial F}{\partial x_m} u(x_m)\right]^2 \qquad \ldots (2.16)$$

Once again, the uncertainty estimates used in this expression can be in terms of individual measurements or mean values, and could include known values of uncertainty $u(x_i)$.

2.2 Measurement procedure

2.2.1 Introduction

In order to monitor meter performance through a statistically based control chart, in general terms the procedure should be carried out as follows:

a) establish statistical control;

b) take measurements in the proving run conducted under the operating conditions required;

c) test the measurements for reliability and use them to create new performance charts, or add to performance charts previously created;

d) add the measurements to control charts in progress, or use the measurements to create new control charts if sufficient measurements have been accumulated in the "learning period".

2.2.2 Statistical control

A measurement taken under undefined or variable operating conditions will not yield meaningful statistics. In order to establish statistical control, great care should be taken that factors such as temperature and flowrate are correctly measured, and that all external influences have been identified.

It is very often difficult to establish statistical control quantitatively. It may be possible, however, to examine performance charts and calculate the maximum allowable range for a set of measurements obtained under the given operating conditions (see 2.1.7). At the very least, it is essential that the measurement procedure is clearly understood and that equipment is operating correctly.

2.2.3 Measurement reliability

A set of n repeated measurements having been obtained, they should be examined for outliers (rogue values). It should be stressed, however, that measurements should not freely be discarded. An attempt should always be made to find a reason for the extreme values, after which corrective action can be taken. Given no further information on the scatter of the measurements, Dixon's or Grubbs' outlier test may be used (see annex D). In the event that an outlier is detected by this means, then it should be disregarded and further measurements obtained. It should also be confirmed that the extreme value was not due to a change in an uncontrolled variable such as temperature or flowrate (see 2.2.2).

The scatter of the K-factor may have already been determined for the operating conditions under which the set of measurements was obtained (see 2.2.4). In that case the uncertainty limits are known, and if a measurement were to fall outside the limit corresponding to 95 % probability, it should be regarded as a rogue value. When only two measurements are available, and their difference exceeds the repeatability (see 2.1.6), then both measurements are suspect. Similarly, the extreme values of a range of n measurements would be suspect if an observed range exceeded the maximum (see 2.1.7).

2.2.4 Performance charts

The performance of a meter can be represented diagrammatically on a performance chart. Figure 1 is an example, in which mean meter factor is given as a function of only one operating condition, namely flowrate. Variability is expressed in figure 1 as the range of n repeated measurements (typically, $n = 5$ or 10), but could also have been expressed as the uncertainty interval.

A separate performance chart should be drawn for each meter and product, and should refer to a stated set of operating conditions (for example range of temperature). In the case of central proving, however, in which it is possible to take measurements covering a wide range of operating conditions on the same class of meter, the "performance charts" may take the form of a matrix or surface in which meter factor is a function of two or more operating variables. (See 3.3.)

2.2.5 Control charts

2.2.5.1 Chart preparation

Following a sufficient learning period (for example 15 sets of proving runs), the true value estimate of K-factor can be represented on a control chart. Figure 2 is an example, in which each entry is a mean of 5 K-factors from four proving runs. The warning and action limits are the uncertainty limits, estimated at the end of the learning period, corresponding to 95 % and 99 % probability, respectively. It would be reasonable to expect that 5 % of the results would lie outside the warning limits and 1 % outside the action limits if the process were in statistical control.