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Paper 1.1

Determination of Measurement Uncertainty for the Purpose of Wet Gas Hydrocarbon Allocation

Per Lunde, Christian Michelsen Research AS (CMR)
Kjell-Eivind Frøysa, Christian Michelsen Research AS (CMR)
Svein Neumann, Norw. Soc. for Oil and Gas Meas. (NFOGM) & ConocoPhillips
Einar Halvorsen, Norwegian Petroleum Directorate (NPD)

Handbook of Uncertainty Calculations - Ultrasonic Fiscal Gas Metering Stations

Per Lunde, Christian Michelsen Research AS (CMR), Bergen, Norway
Kjell-Eivind Frøysa, Christian Michelsen Research AS (CMR), Bergen, Norway
Svein Neumann, Norw. Soc. for Oil and Gas Meas. (NFOGM) & ConocoPhillips, Norway
Einar Halvorsen, Norwegian Petroleum Directorate (NPD), Stavanger, Norway

SUMMARY

A "*Handbook of uncertainty calculations - Ultrasonic fiscal gas metering stations"* [1] has been developed in a cooperation between NFOGM, NPD and CMR, addressing fiscal metering of gas using multipath ultrasonic transit time flow meters (USM). The many different approaches to calculating the uncertainty of ultrasonic gas metering stations have been a source of confusion; - varying practice in this respect has definitely been experienced. The intention of the present initiative has been that a handbook together with a spreadsheet program *EMU - USM Fiscal Gas Metering Station*, based upon the principles laid down in the "*Guide to the expression of uncertainty in measurement (GUM)"* [2] and ISO/DIS 5168 [3], would satisfy the need for a modern method of uncertainty evaluation in the field of ultrasonic fiscal gas measurement.

In the present work, calculation of the expanded uncertainty of the following four metering station measurands is addressed: the actual volume flow rate, the standard volume flow rate, the mass flow rate, and the energy flow rate. The analytical uncertainty model accounts for metering station instrumentation such as pressure transmitter, temperature element and transmitter, compressibility factor calculation (from gas chromatograph analysis), density measurement (vibrating element densitometer), calorific value measurement, and a flow calibrated multipath ultrasonic gas flow meter (USM). The expanded uncertainty of each of these measurands and instruments can be calculated and analyzed, isolated and combined (for the metering station). The basis for the *Handbook* and the program is described, together with an example of a metering station uncertainty evaluation.

1. INTRODUCTION

1.1 Uncertainty Evaluation of Ultrasonic Gas Flow Metering Stations

Regulations relating to fiscal measurement of oil and gas [4,5,6] require that the overall measurement uncertainty is documented to be within defined limits. However, the different methods used have given different results. A consistent and standardised method of uncertainty evaluation has been required, so that different measurement systems could be directly and reliably compared.

In 1993 the ISO report "*Guide to the expression of uncertainty in measurement"* (commonly referred to as the *"Guide*" or the "*GUM"*) was published, with a revision in 1995. This report is providing general rules for evaluating and expressing uncertainty in measurement, intended for a broad scope of measurement areas. The Norwegian Petroleum Directorate (NPD) and the Norwegian Society for Oil and Gas Measurement (NFOGM), together with Christian Michelsen Research (CMR), felt that a user-friendly handbook together with a spreadsheet program, based upon the principles laid down in the *GUM*, would satisfy the need for a modern method of uncertainty evaluation in the field of fiscal oil and gas measurement.

In 1999 a "*Handbook of uncertainty calculations - Fiscal metering stations"* [7] was developed by the three partners, addressing fiscal metering of oil using turbine meters, and fiscal metering of gas using orifice meters. On background of the significant and increasing interest for the use of multipath ultrasonic transit time flow meters (USM) for fiscal metering of gas, a second handbook was developed in 2001, addressing the uncertainty of fiscal gas metering stations using ultrasonic meters [1].

1.2 The *Handbook*

The *Handbook of uncertainty calculations - USM fiscal gas metering stations* [1] (for convenience here referred to as the *Handbook)* consists of the *Handbook* itself and the Microsoft Excel program *EMU - USM Fiscal Gas Metering Station* for performing uncertainty calculations of fiscal gas metering stations based on flow calibrated USM flow meters, and individual instruments of such stations (cf. Section 2).

The USM fiscal gas metering stations addressed in the *Handbook* are primarily taken to be built and operated according to NPD regulations [4]. For USM fiscal metering of gas, the NPD regulations refer to e.g. the NORSOK I-104 national standard [5] and the AGA Report No. 9 [6] as recognised standards ("accepted norms"). Both the NPD regulations and the NORSOK I-104 standard refer to the *GUM* [2] as the "accepted norm" with respect to uncertainty analysis.

Consequently, the *Handbook* and the computer program *EMU - USM Fiscal Gas Metering Station* are based primarily on the recommended procedures in the *GUM*. They are also considered to be in consistence with the proposed revision of ISO 5168 [3] (also based on the *GUM*).

With respect to uncertainty evaluation and documentation, refs. [3,4] state that the expanded uncertainty of the metering station shall be specified at a 95 % confidence level, using a coverage factor k = 2. Consequently, for output expanded uncertainties k = 2 is set as a fixed value in the program. For input expanded uncertainties, however, k is set by the user for each input uncertainty value (depending on the confidence level of the input uncertainty in question).

The uncertainty model for the USM gas metering station used here is based on an analytical approach. That is, the uncertainty models involving the USM, pressure transmitter, temperature element/transmitter, densitometer, calculation of compressibility factors, and calorimeter, are fully analytical, with expressions given and documented for the model and the sensitivity coefficients. The model is treated at a sufficiently generic level so that all relevant gas USM types are covered (cf. e.g. [8-10]), irrespective of path configuration, including non-reflecting path as well as reflecting path USMs. The intention has been to meet as far as possible manufacturer data specified today with respect to instrument uncertainties, including the USM. The work builds on earlier developments in this field [11-15], see also [16].

The *Handbook* is intended to provide a practical approach to the field of uncertainty calculations of ultrasonic fiscal gas metering stations. It is primarily written for experienced users and operators of fiscal gas metering stations, manufacturers of ultrasonic gas flow meters, engineering personnel as well as others with interests within the field. It has been the intention that the Excel program may be run without needing to read much of the *Handbook*, such as the theory part. However, Chapter 5 in the *Handbook* which gives an overview of the program, as well as Chapter 4 which - through an uncertainty evaluation example - provides some guidelines for specifying input parameters and uncertainties to the program, may be useful to read together with running the program for the first time.

2. USM FISCAL GAS METERING STATION

Consider a gas metering station equipped with instrumentation as specified in Table 1.

Table 1. USM fiscal gas metering station equipment considered in the *Handbook*. Included is also example instrumentation used for uncertainty evaluation of a fiscal gas metering station in Section 5.

Measurement	Instrument
Ultrasonic meter (USM)	Multipath flow calibrated transit time USM. Otherwise arbitrary.
Flow computer	Arbitrary.
Pressure (static), P	Pressure transmitter. Otherwise arbitrary. (Example: Rosemount 3051P Reference Class Pressure Transmitter [17])
Temperature, T	Temperature element and transmitter. Otherwise arbitrary. (Example: Pt 100 4-wire RTD element / Rosemount 3144 Smart Temp. Transm. [17])
Density, ρ	On-line installed vibrating element gas densitometer. Otherwise arbitrary. (Example: Solartron 7812 Gas Density Transducer [18])
Compressibility factors, Z and Z_0	Calculated from GC measurements / equations of state. Otherwise arbitrary. (Example: AGA-8(92) [19] for Z (line cond.), ISO 6976 [20] for Z_0 (std. ref. cond.))
Superior calorific value, H_s	Calorimeter (combustion method). Otherwise arbitrary.

For fiscal gas metering stations, four flow rates are in question [5]:

- Actual volume flow rate (i.e. the volumetric flow rate at line conditions), q_v,
- Standard volume flow rate (i.e., the volumetric flow rate at standard reference conditions), Q,
- Mass flow rate, q_m, and
- Energy flow rate, q_e.

These are given as[1]

$$q_v = 3600 \cdot K \cdot q_{USM} \quad [\text{m}^3/\text{h}] , \qquad Q = \frac{PT_0Z_0}{P_0TZ} q_v \quad [\text{Sm}^3/\text{h}] , \tag{1}$$

$$q_m = \rho q_v \quad [\text{kg/h}] , \qquad q_e = H_S Q \quad [\text{MJ/h}] ,$$

respectively. Here, q_{USM} is the axial volumetric flow rate indicated by the USM under field operation (line conditions), before the correction factor K is applied. Subscript *"0"* at a quantity is used to denote the value of the quantity at standard reference conditions (1 atm. and 15 °C).

The correction factor $K \equiv f(K_1, K_2, ...K_M)$ is some function f of M meter factors K_j, where the meter factors are obtained by flow calibrating the USM at M different nominal test flow rates ("calibration points") [1]. Typically, M is 4 to 6, and K is usually flow rate dependent. Methods for calculation of the correction factor K from the M meter factors K_j are discussed e.g. in [1,6], such as various types of single-factor and multi-factor corrections[2]. The uncertainty model described here covers any of these methods. In fact, for use of the uncertainty program one does not need to know K nor the method used for calculating K. It is sufficient to know the corrected relative deviation after K has been applied, $Dev_{C,j}$, defined by Eq. (8).

The functional relationships of the USM, pressure transmitter, temperature element/transmitter and gas densitometer, which form the basis for the uncertainty model described in Section 3, are described in [1]. Due to space limitations these are not given here.

3. UNCERTAINTY MODEL OF THE GAS METERING STATION

For the four measurands given in Eq. (1), the relative combined standard uncertainties are given as [1]

$$E_{q_v}^2 = E_{cal}^2 + E_{USM}^2 + E_{comm}^2 + E_{flocom}^2 , \qquad E_Q^2 = E_P^2 + E_T^2 + E_{Z/Z_0}^2 + E_{q_v}^2 ,$$

$$E_{q_m}^2 = E_\rho^2 + E_{q_v}^2 , \qquad E_{q_e}^2 = E_{H_S}^2 + E_Q^2 , \tag{2}$$

respectively. Here, E_{cal} and E_{USM} are the relative standard uncertainties of the USM flow calibration and the USM in field operation, respectively. E_{comm} and E_{flocom} are the relative standard uncertainties due to signal communication and the flow computer. E_P, E_T, E_ρ, E_{H_S} and E_{Z/Z_0} are the relative standard uncertainties of the pressure, temperature, density and calorific value measurement, and the compressibility factor calculations, respectively. The corresponding relative expanded uncertainties at a 95 % confidence level are obtained by multiplying with the coverage factor k = 2 (assuming a normal probability distribution).

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[1] Alternative methods for calculation of Q, q_m and q_e (related to the use of various instrument configurations in various gas metering stations) are discussed in [1]. Only the methods given by Eqs. (1) are accounted for in the present version of the uncertainty program, but the alternative methods may be included in a possible future upgrade.

[2] Single-factor correction methods for calculation of the correction factor K include e.g. (a) the flow-weighted mean error (FWME) [6], (b) the weighted mean error (WME) [22], and average meter factor methods. Multi-factor correction methods include e.g. (a) piecewise linear interpolation [6], (b) multi-point (higher order) polynomial algorithms [6], and (c) regression analysis methods.

The derivation underlying the uncertainty model given by Eqs. (2) is rather comprehensive, and for details it is referred to [1]. The model has been obtained by a detailed analysis of correlated and uncorrelated effects in the USM, such as for the USM in field operation vs. flow calibration, between the various acoustic paths of the USM, between upstream and downstream signal propagation in a given acoustic path (correlated and uncorrelated transit time contributions), etc. Thus, elimination of systematic effects in the USM by flow calibration is accounted for, so that these do not contribute to the metering station uncertainty. The analysis is made in compliance with the procedure for evaluating and expressing uncertainties recommended in [2][3]. The various terms involved in Eq. (2) are further described in the following.

3.1 Pressure Transmitter Uncertainty

The relative combined standard uncertainty of the pressure measurement is given as $E_P \equiv u_c(\hat{P})/\hat{P}$, where [1]

$$u_c^2(\hat{P}) = u^2(\hat{P}_{transmitter}) + u^2(\hat{P}_{stability}) + u^2(\hat{P}_{RFI}) + u^2(\hat{P}_{temp}) + u^2(\hat{P}_{atm}) + u^2(\hat{P}_{vibration}) + u^2(\hat{P}_{power}) + u^2(\hat{P}_{misc}) \quad (3)$$

gives the combined standard uncertainty of the pressure measurement[4]. The eight terms at the right hand side of Eq. (3) account, respectively, for uncertainties related to (a) the pressure transmitter (hysteresis, terminal-based linearity, repeatability, pressure calibration laboratory), (b) stability of the pressure transmitter, (c) radio-frequency interference (RFI) effects, (d) temperature effects, (e) atmospheric pressure, (f) vibration effects, (g) power supply effects, and (h) miscellaneous effects (mounting, etc.). With exception for (e), information on these input uncertainties are normally to be provided by the manufacturer or calibration laboratory, cf. e.g. [17].

3.2 Temperature Element / Transmitter Uncertainty

The relative combined standard uncertainty of the temperature measurement is given as $E_T \equiv u_c(\hat{T})/\hat{T}$, where [1]

$$u_c^2(\hat{T}) = u^2(\hat{T}_{elem,transm}) + u^2(\hat{T}_{stab,transm}) + u^2(\hat{T}_{RFI}) + u^2(\hat{T}_{temp}) + u^2(\hat{T}_{stab,elem}) + u^2(\hat{T}_{vibration}) + u^2(\hat{T}_{power}) + u^2(\hat{T}_{cable}) + u^2(\hat{T}_{misc}) \quad (4)$$

gives the combined standard uncertainty of the temperature measurement. The nine terms at the right hand side of Eq. (4) account, respectively, for uncertainties related to (a) the temperature element and transmitter calibrated as a unit, (b) stability of the temperature transmitter, (c) RFI effects, (d) temperature effects, (e) stability of the Pt100 element, (f) vibration effects, (g) power supply effects, (h) lead resistance effects, and (i) miscellaneous effects. Information on these input uncertainties are normally to be provided by the instrument manufacturer or calibration laboratory, cf. e.g. [17].

3.3 Compressibility Factor Uncertainties

The relative combined standard uncertainty of the compressibility factor calculations is given by

$$E_{Z/Z_0}^2 = E_{Z,mod}^2 + E_{Z0,mod}^2 + (E_{Z,ana} - E_{Z0,ana})^2 \, . \quad (5)$$

[3] With respect to symbol notation, the *Handbook* deviates in a few cases from the recommendations given in [2], mainly for practical reasons. E.g., for relative standard uncertainties and rel. sensitivity coefficients, the symbols "E_x" and "s_x^*" are used in [1], whereas the recommended symbols in [2] are "$u(x)/x$" and "c_x^*", respectively.

[4] To distinguish between a quantity and an estimated value of the quantity, the symbol "$\hat{x}$" (the "hat notation") is used here to denote the estimated value of the quantity "x".

The two first terms at the right hand side of Eq. (5) account for the *model uncertainties* (i.e. the uncertainties of the equation of state(s) used for calculation of $\hat{Z}$ and $\hat{Z}_0$, e.g. the AGA-8(92) equation [19], the ISO 6976 method [20] or the ISO/GERG method [21]). This includes the uncertainty of the equation of state itself, and the uncertainty of the "basic data" underlying the (empirical) equation of state. The model uncertainty depends on pressure and temperature. Uncertainty information may be found in documentation of the equation of state, such as for [19] and [20].

The two latter terms in Eq. (5) (in the parenthesis) represent the *analysis uncertainties,* due to inaccurate determination of the gas composition at line and standard conditions, e.g. using gas chromatography (GC). This includes the uncertainty of the GC measurement itself, and possibly natural variations in gas composition. Both contributions will depend on gas composition, pressure and temperature. Examples have shown that this uncertainty contribution can be all from negligible to around 1 %. It may be determined e.g. using a Monte Carlo type of simulation, where the gas composition is varied within its uncertainty limits [1].

The model uncertainties are here taken to be mutually uncorrelated, whereas the analysis uncertainties act as systematic effects, and are taken to be mutually correlated. A discussion is given in [1].

3.4 Densitometer Uncertainty

The relative combined standard uncertainty of the density measurement is given as $E_\rho \equiv u_c(\hat{\rho})/\hat{\rho}$, where [1]

$$\begin{aligned} u_c^2(\hat{\rho}) = {} & s_{\rho_u}^2 u^2(\hat{\rho}_u) + u^2(\hat{\rho}_{rept}) + s_{\rho,T}^2 u_c^2(\hat{T}) + s_{\rho,T_d}^2 u^2(\hat{T}_d) + s_{\rho,T_c}^2 u^2(\hat{T}_c) \\ & + s_{\rho,K_d}^2 u^2(\hat{K}_d) + s_{\rho,\tau}^2 u^2(\hat{\tau}) + s_{\rho,c_c}^2 u^2(\hat{c}_c) + s_{\rho,c_d}^2 u^2(\hat{c}_d) \\ & + s_{\rho,\Delta P_d}^2 u^2(\Delta\hat{P}_d) + s_{\rho,P}^2 u_c^2(\hat{P}) + u^2(\hat{\rho}_{temp}) + u^2(\hat{\rho}_{misc}) \end{aligned} \qquad (6)$$

gives the combined standard uncertainty of the density measurement. In addition to the usual frequency relationship regression curve, the functional relationship of the vibrating-element gas densitometer used here accounts for temperature correction, VOS (velocity of sound) correction, and installation correction (on-line installation, in a by-pass line) [1].

The 13 terms at the right hand side of Eq. (6) account, respectively, for uncertainties related to (a) the indicated (uncorrected) density (calibration laboratory instruments, reading error during calibration, hysteresis, etc.) (also referred to as the "densitometer accuracy" [18]), (b) repeatability, (c) temperature measurement in the line, T, (d) temperature measurement in the densitometer, T_d, (e) temperature at calibration, T_c, (f) transducer constant used in VOS correction, K_d, (g) periodic time estimate, τ, (h) calibration gas VOS estimate, c_c, (i) densitometer gas VOS estimate, c_d, (j) possible pressure deviation from densitometer to line conditions, ΔP_d, (k) pressure measurement in the line, P, (l) temperature correction model, and (m) miscellaneous effects (stability, reading error, deposits, corrosion, liquid condensation, vibrations, power supply variations, self-induced heat, flow in by-pass line, gas viscosity, etc.). The various $s_{x,y}$ terms are sensitivity coefficients given in [1].

Figures for the input uncertainties $u(\hat{\rho}_u)$, $u(\hat{\rho}_{rept})$, $u(\hat{T}_c)$, $u(\hat{\tau})$, $u(\hat{\rho}_{temp})$ and contributions to $u(\hat{\rho}_{misc})$ should normally be provided by the instrument manufacturer, cf. e.g. [18]. Figures for $u(\hat{K}_d)$, $u(\hat{c}_c)$, $u(\hat{c}_d)$ and $u(\Delta\hat{P}_d)$ may be obtained from the manufacturer or by other sources, cf. [1]. $u_c(\hat{P})$, $u_c(\hat{T})$ and $u(\hat{T}_d)$ are given by Eqs. (3)-(4).

3.5 Calorific Value Uncertainty

The relative combined standard uncertainty of the superior (gross) calorific value is defined as $E_{H_S} \equiv u(\hat{H}_S)/\hat{H}_S$. In the current version of the EMU program (cf. Section 4) E_{H_S} is used as input uncertainty. As a simplification, it has been assumed here that the calorific value estimate, $\hat{H}_s$, is uncorrellated to the standard volumetric flow rate, $\hat{Q}$, cf. Eq. (1). As the conversion from line conditions to standard reference conditions for the volumetric flow is assumed here to be carried out using a gas chromatograph (calculation of Z and Z_0, cf. Table 1), the calorific value is thus implicitly assumed to be measured using a method which is uncorrelated with gas chromatography (such as e.g. a calorimeter). Information on E_{H_S} may be provided by the instrument manufacturer, or taken to be a typical, representative value.

3.6 Flow Calibration Uncertainty

The relative combined standard uncertainty of the USM flow calibration is given by [1]

$$E_{cal}^2 \equiv E_{q_{ref,j}}^2 + E_{K_{dev,j}}^2 + E_{rept,j}^2 . \tag{7}$$

The three terms at the right hand side of Eq. (7) account, respectively, for uncertainties related to (a) the reference flow measurement at test flow rate no. *j, j = 1,…,M* (representing the uncertainty of the flow calibration laboratory, including reproducibility), (b) the deviation factor, and (c) the repeatability of the USM flow calibration measurement at test flow rate no. *j*, *j* = 1, …, *M* (due to random transit time effects, including repeatability of the flow laboratory reference measurement). In practice $E_{rept,j}$ represents the relative standard deviation of the spread of measured flow rates, at test flow rate no. *j*, and is to be specified by the USM manufacturer.

It can be shown [1] that the relative standard uncertainty of the deviation factor may be calculated as

$$E_{K_{dev,j}} = \frac{1}{\sqrt{3}}\left|\frac{Dev_{C,j}}{\hat{K}_{dev,j}}\right| \approx \frac{Dev_{C,j}}{\sqrt{3}}, \qquad Dev_{C,j} = \frac{Kq_{USM,j} - q_{ref,j}}{q_{ref,j}}, \qquad j = 1,\ ...,\ M, \tag{8}$$

where $q_{USM,j}$ is the axial volumetric flow rate measured by the USM under flow calibration, at test flow rate no. *j*, $q_{ref,j}$ is the corresponding reference value for the axial volumetric flow rate under flow calibration (as measured by the flow calibration laboratory), $Dev_{C,j}$ is the corrected relative deviation at this test flow rate (i.e. the relative deviation after multiplication with the correction factor, *K*), and $K_{dev,j} = 1 + Dev_{C,j}$ is the deviation factor. The deviation data $Dev_{C,j}$, *j = 1, …, M*, are to be specified by the USM manufacturer at the *M* test flow rates.

3.7 USM Field Operation Uncertainty

The relative combined standard uncertainty of the USM in field operation is given by [1]

$$E_{USM}^2 \equiv E_{rept}^2 + E_{USM,\Delta}^2 + E_{misc}^2 . \tag{9}$$

The three terms at the right hand side of Eq. (9) account, respectively, for uncertainties related to (a) repeatability of the USM measurement in field operation, at the flow rate in question (due to random transit time effects), (b) systematic effects in field operation of the USM, due to change of conditions from flow calibration to field operation, and (c) miscellaneous systematic effects on the USM field measurement which are not eliminated by flow calibration, and which are not covered by other uncertainty terms accounted for here (e.g. inaccuracy of the USM functional relationship (the underlying mathematical model), etc.).

In Eq. (9), the "USM field repeatability" term is given by

$$E_{rept}^2 \equiv 2\sum_{i=1}^{N}(s_{t1i}^* E_{t1i,U})^2 \ . \tag{10}$$

The relative sensitivity coefficient s_{t1i}^* is given in [1]. $E_{t1i,U}$ is the relative standard uncertainty of those contributions to the transit times of path no. *i* which are uncorrelated with respect to upstream and downstream propagation. It is given as

$$E_{t1i,U} = u(\hat{t}_{1i}^{random})/\hat{t}_{1i} \ , \tag{11}$$

where $\hat{t}_{1i}$ is the upstream transit time of path no. *i*, and and $u(\hat{t}_{1i}^{random})$ is the standard uncertainty due to in-field random effects on transit times (after possible signal averaging), such as (a) turbulence, (b) incoherent noise (due to pressure reduction valves, RFI, vibrations, etc.), (c) coherent noise (acoustical and electrical cross-talk, acoustic reverberation, other signal interference), (d) finite clock resolution, (e) electronics stability (possible random effects), (f) possible random effects in signal detection/processing (e.g. erroneous signal period identification), and (g) power supply variations. In practice, at a given flow rate, $u(\hat{t}_{1i}^{random})$ represents the standard deviation of the spread of measured transit times in path no. *i*. Similarly, E_{rept} represents the standard deviation of the spread of measured flow rates, at the actual flow rate. One of these should be specified by the USM manufacturer.

In Eq. (9), the "systematic USM field effects" term can be expressed by[5]

$$E_{USM,\Delta}^2 \equiv E_{body,\Delta}^2 + E_{time,\Delta}^2 + E_{I,\Delta}^2 \ , \tag{12}$$

where the three terms at the right hand side of Eq. (12) account, respectively, for uncertainties related to (a) possible uncorrected change of the USM meter body dimensions (radius, lateral chord positions, inclination angles) from flow calibration to field operation, caused by possible deviation in *P*, *T* between flow calibration and field operation, (b) possible uncorrected systematic effects on the transit times caused e.g. by deviation in conditions from flow calibration to field operation (*P*, *T*, transducer deposits, transducer ageing, etc), and (c) possible change of installation conditions from flow calibration to field operation (related to the USM integration method).

In Eq. (12), the "meter body uncertainty" term can be shown [1] to be given as

$$E_{body,\Delta} \equiv E_{rad,\Delta} + E_{chord,\Delta} + E_{angle,\Delta} \ , \tag{13a}$$

where

$$E_{rad,\Delta} \equiv s_R^* E_{R,\Delta} , \qquad E_{chord,\Delta} \equiv \sum_{i=1}^{N} sign(\hat{y}_i) s_{yi}^* E_{yi,\Delta} \ , \qquad E_{angle,\Delta} \equiv \sum_{i=1}^{N} sign(\hat{\phi}_i) s_{\phi i}^* E_{\phi i,\Delta} \ , \tag{13b}$$

$$E_{R,\Delta}^2 = E_{yi,\Delta}^2 = E_{KP}^2 + E_{KT}^2 , \qquad E_{\phi i,\Delta} = \frac{B \sin 2\hat{\phi}_{i0}}{2\hat{\phi}_{i0}} E_{KP} \ . \tag{13c}$$

Here, s_R^*, s_{yi}^* and $s_{\phi i}^*$ are relative sensitivity coefficients given in [1], ϕ_{i0} is the inclination angle of path no. *i* at "dry calibration" conditions, *N* is the number of acoustic paths in the USM, and *B* is a constant defined in [1]. E_{KP} and E_{KT} are the relative standard uncertainties of the radial pressure and temperature correction factors for the USM meter body, K_P and K_T, respectively, given as

$$E_{KP} \equiv u_c(\hat{K}_P)/\hat{K}_P \ , \qquad u_c(\hat{K}_P) = \sqrt{(\Delta\hat{P}_{cal})^2 u^2(\hat{\beta}) + \hat{\beta}^2 u_c^2(\Delta\hat{P}_{cal})} \ , \tag{14a}$$

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[5] The subscript "Δ" denotes that *only deviations relative to the conditions at the flow calibration* are to be accounted for in the expressions involving this subscript. That means, uncertainty contributions which are practically eliminated at flow calibration, are *not* to be included in these expressions.

$$E_{KT} \equiv u_c(\hat{K}_T)/\hat{K}_T \ , \qquad u_c(\hat{K}_T) = \sqrt{(\Delta\hat{T}_{cal})^2 u^2(\hat{\alpha}) + \hat{\alpha}^2 u_c^2(\Delta\hat{T}_{cal})} \ , \tag{14b}$$

where $u(\hat{\alpha})$ and $u(\hat{\beta})$ are the standard uncertainties of the coefficients of linear temperature and pressure expansion of the meter body material (usually steel), α and β, respectively. ΔP_{cal} and ΔT_{cal} are the difference in gas pressure and temperature between line and flow calibration conditions, respectively. For calculation of the combined standard uncertainties of ΔP_{cal} and ΔT_{cal}, two cases are addressed here. In cases for which *P* and *T* corrections of the meter body are *not* used, these uncertainties are determined by the *span* of ΔP_{cal} and ΔT_{cal}, so that

$$u_c(\Delta\hat{P}_{cal}) = \Delta\hat{P}_{cal}/\sqrt{3} \ , \quad u_c(\Delta\hat{T}_{cal}) = \Delta\hat{T}_{cal}/\sqrt{3} \ . \tag{15}$$

In cases where *P* and *T* corrections of the meter body *are* used, these uncertainties are determined by the *measurement uncertainties* of ΔP_{cal} and ΔT_{cal}, so that

$$u_c(\Delta\hat{P}_{cal}) = \sqrt{2}u_c(\hat{P}) \ , \quad u_c(\Delta\hat{T}_{cal}) = \sqrt{2}u_c(\hat{T}) \ , \tag{16}$$

where $u_c(\hat{P})$ and $u_c(\hat{T})$ are given by Eqs. (3) and (4). Details are given in [1][6].

In Eq. (12), the "systematic transit time effects" term is given as

$$E_{time,\Delta} \equiv \sum_{i=1}^{N} \left(s_{t1i}^{*} E_{t1i,C}^{\Delta} + s_{t2i}^{*} E_{t2i,C}^{\Delta} \right) \ . \tag{17}$$

$E_{t1i,C}^{\Delta}$ and $E_{t2i,C}^{\Delta}$ are the relative standard uncertainties of uncorrected systematic transit time effects on upstream and downstream propagation of acoustic path no. *i*, due to possible deviation in pressure and/or temperature from flow calibration to field operation, defined as

$$E_{t1i,C}^{\Delta} = u(\hat{t}_{1i}^{systematic})/\hat{t}_{1i} \ , \qquad E_{t2i,C}^{\Delta} = u(\hat{t}_{2i}^{systematic})/\hat{t}_{2i} \ . \tag{18}$$

$\hat{t}_{1i}$ and $\hat{t}_{2i}$ are the upstream and downstream transit times of path no. *i*, and $u(\hat{t}_{1i}^{systematic})$ and $u(\hat{t}_{2i}^{systematic})$ are the standard uncertainties of uncorrected systematic effects in these transit times. Information on these input uncertainties should be provided by the USM manufacturer. s_{t1i}^{*} and s_{t2i}^{*} are relative sensitivity coefficients defined in [1].

Such systematic transit time effects may be due to (a) cable/electronics/transducer/diffraction time delay (due to line pressure and temperature effects, ambient temperature effects, drift, effects of possible transducer exchange), (b) possible Δt-correction (line pressure and temperature effects, ambient temperature effects, drift, reciprocity effects, effects of possible transducer exchange), (c) possible systematic effects in signal detection/processing, (d) possible cavity time delay correction effects, (e) possible transducer deposits (lubricant oil, grease, wax, etc.), and (f) sound refraction (flow profile effects ("ray bending")).

In Eq. (12), the "installation effects" term $E_{I,\Delta}$ is related to the USM integration method, and serves as an input uncertainty. Information on $E_{I,\Delta}$ should be provided by the USM manufacturer. Such installation effects on the USM integration uncertainty may be due to (a) change of *axial flow velocity profile* (from flow calibration to field operation), and (b) change of *transversal flow velocity profiles* (from flow calibration to field operation). These may both be due to (*i*) possible different pipe bend configuration upstream of the USM, (*ii*) possible different in-flow profile to the upstream pipe bend, (*iii*) possible change of meter orientation relative to pipe

[6] Ref. [1] also includes an overview and discussion of methods used for *P* and *T* correction of the USM meter body.

bends, (*iv*) possible changed wall roughness over time (corrosion, wear, pitting, etc.), in the pipe and meter body, and (*v*) possible wall deposits / contamination in the pipe and meter body (grease, liquid, lubricants), etc.

3.8 Signal Communication and Flow Computer Uncertainty

In Eq. (1), the relative uncertainty term E_{comm} accounts for the uncertainties due to the signal communication between the USM field electronics and the flow computer (e.g. the flow computer calculation of frequency in case of analog frequency output). E_{flocom} accounts for the uncertainty of the flow computer calculations. Both should be specified by the USM manufacturer, and are normally relatively small.

4 MICROSOFT EXCEL PROGRAM "*EMU - USM FISCAL GAS METERING STATION*"

A PC program has been implemented based on the uncertainty model for the metering station described in Section 3. The program *EMU - USM Fiscal Gas Metering Station* is implemented as a Microsoft Excel 2000 spreadsheet.

The program calculates the expanded and relative expanded uncertainties of a gas metering station which is based on a flow calibrated USM, for the four measurands in question, q_v, Q, q_m and q_e.

In addition to calculation/plotting/reporting of the expanded uncertainty of the gas metering station and the individual instruments of the station, the Excel program can be used to calculate, plot and analyse the relative importance of the various contributions to the uncertainty budget for the various instruments of the metering station (using bar-charts).

For several of the instruments and procedures involved in the metering station, an implementation strategy has been chosen which enables the user to give uncertainty input at two levels: (1) an *"overall level"*, and (2) a more *"detailed level"*, cf. Table 2. This provides a useful flexibility in use of the program.

At the *overall level*, the user specifies the combined standard uncertainty of the instrument in question directly as input to the program. It is left to the user to calculate and document this uncertainty figure. This option is general, and covers any method of obtaining the uncertainty figure[7].

At the *detailed level*, the combined standard uncertainty of the instrument in question is calculated by the program, from more basic input for the instrument provided e.g. by the instrument manufacturer and calibration laboratory, as outlined in Section 3.

[7] The "overall level" option may be of interest in several cases, such as e.g.: (a) if the user wants a "simple" and quick evaluation of the influence of an instrument uncertainty on the expanded (overall) uncertainty of the gas metering station, (b) in case of a different installation of the gas densitometer (e.g. in-line), (c) in case of a different gas densitometer functional relationship, (d) in case of density measurement using GC analysis and calculations instead of densitometer measurement, or (e) in case the input used at the "detailed level" does not fit sufficiently well to the type of input data / uncertainties which are relevant for e.g. the pressure transmitter or temperature element/transmitter at hand.

Table 2. Uncertainty model contributions, and optional levels for specification of input uncertainties to the program *EMU - USM Fiscal Gas Metering Station*.

Uncertainty contribution	Overall level	Detailed level
Pressure measurement uncertainty	✓	✓
Temperature measurement uncertainty	✓	✓
Compressibility factor uncertainties		✓
Density measurement uncertainty	✓	✓
Calorific value measurement uncertainty	✓	
USM flow calibration uncertainty		✓
USM field uncertainty	✓	✓
Signal communication and flow computer calculations	✓	

With respect to *USM flow calibration* and *USM field operation*, the level for specification of input uncertainties at the detailed level is adapted to data from "dry calibration" / flow calibration / testing of USMs to be provided by the USM manufacturer. In particular this concerns:

(1) USM flow calibration:

- **Calibration laboratory.** The user specifies the uncertainty of the flow calibration laboratory reference measurement for the volumetric flow rate (incl. reproducibility), $E_{ref,j}$, cf. Eq. (7). It can be given in the program to be flow rate dependent.
- **Repeatability.** The user specifies the repeatability (relative standard deviation) of the indicated USM flow rate measurement at flow calibration, $E_{rept,j}$, cf. Eq. (7). That is, the combined repeatability of the USM and the flow calibration laboratory reference measurement. It can be given in the program to be flow rate dependent.
- **Deviation factor.** The user specifies the corrected relative deviation $Dev_{C,j}$ at each test flow rate ("calibration point"), i.e. the relative deviation from reference after multiplication with the correction factor, *K*, cf. Eq. (8).

(2) USM field operation:

- **Repeatability.** The user specifies either (a) the repeatability (relative standard deviation) of the indicated USM flow rate measurement in field operation, E_{rept} , or (b) the repeatability (standard deviation) of the measured transit times, $u(\hat{t}_{1i}^{random})$, cf. Eqs. (10) and (11), respectively. Both can be given in the program to be flow rate dependent.
- **Meter body parameters.** The user specifies whether correction for pressure and temperature effects is used or not for the USM meter body, and the uncertainties of the temperature and pressure expansion coefficients, $u(\hat{\alpha})$ and $u(\hat{\beta})$. Cf. Eqs. (13)-(16).
- **Systematic transit time effects.** The user specifies the uncertainty of uncorrected systematic effects on the measured upstream and downstream transit times, $u(\hat{t}_{1i}^{systematic})$ and $u(\hat{t}_{2i}^{systematic})$, cf. Eq. (18).
- **Integration method (installation effects).** The user specifies the uncertainty due to installation effects, $E_{I,\Delta}$, cf. Eq. (12).

With respect to the USM technology, the program can thus be run in two modes:

(A) Completely meter independent, and
(B) Weakly meter dependent.

Mode (A) corresponds to choosing the overall level for the USM field uncertainty (both for the repeatability and the systematic deviation re. flow calibration). Mode (B) corresponds to choosing the "detailed level".

By "weakly meter dependent" is here meant that the bore diameter, number of paths and the number of reflections for each path are to be known. However, actual values for the inclination angles, lateral chord positions and integration weights do not need to be known. Only very approximate values for these quantities are needed (used for calculation of certain sensitivity coefficients).

5 UNCERTAINTY EVALUATION EXAMPLE

As an example of evaluation of the expanded uncertainty of a USM fiscal gas metering station using the program described in Section 4, consider the typical North Sea metering station instrumentation example given in Table 1: 12" pipeline, a Rosemount 3051P pressure transmitter [17], a Pt 100 4-wire RTD element and a Rosemount 3144 temperature transmitter [17], and a Solartron 7812 Gas Density Transducer [18]. The flow computer, gas chromatograph and calorimeter are arbitrary (unspecified). The USM is a 4-path meter with parallel chords, non-reflecting paths and Gauss-Jacobi integration. A typical North Sea gas composition is considered, at conditions of 100 bara and 50 °C. Flow calibration conditions are 50 bara and 10 °C.

Evaluation of e.g. the mass flow rate uncertainty involves the USM, the Solartron densitometer, the signal communication / flow computer, as well as the gas parameters. The "detailed level" of input is used here. Input uncertainties for the densitometer are taken partly from [18], partly from other sources (when data have not been available in [18]), cf. [1]. For the USM flow calibration, three input uncertainties are in question, cf. Eq. (7): The flow laboratory uncertainty is taken to be $kE_{q_{ref,j}}$ = 0.3 %[8]. The repeatability is taken to be $kE_{rept,j}$ = 0.2 %, constant over the flow rate range (which is probably simplified), as a typical value specified in data sheets [8-10]. For the deviation factor uncertainty, $kE_{K_{dev,j}}$, a flow calibration example given in the AGA-9 report [6] is used as a basis, cf. [1]. In that example the correction factor *K* is calculated on basis of the flow-weighted mean error (FWME), as a single, constant value over the flow rate range.

For the USM in field operation, several input uncertainties are in question, cf. Eqs. (10), (11), (12), (13) and (18). The USM field repeatability is taken to be kE_{rept} = 0.2 %, constant over the flow rate range (which is probably simplified), as a typical value specified in data sheets [8-10]. On lack of manufacturer data, the installation effects uncertainty is taken to be $kE_{I,\Delta}$ = 0.3 %, as a tentative example value. Similarly, on lack of data, the uncertainty of uncorrected systematic effects on the measured upstream and downstream transit times, $k \cdot u(\hat{t}_{1i}^{systematic})$ and $k \cdot u(\hat{t}_{2i}^{systematic})$, are given as 600 and 590 ns, respectively, as a tentative example. The case is considered where pressure and temperature correction is not used for the meter body. The uncertainties of the temperature and pressure expansion coefficients $k \cdot u(\hat{\alpha})$ and $k \cdot u(\hat{\beta})$ are set to 20 %, as example values. Details are given in [1].

Fig. 1 shows the relative expanded uncertainty of the mass flow rate measurement (together with the mass flow rate itself), plotted over the flow velocity range 0.4 to 10 m/s. The relative expanded uncertainty is calculated at *M* = 6 flow velocities for which flow calibration has been performed, and straight lines are drawn in-between these points.

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[8] In the present calculation example given here, all input uncertainties given in the text are taken to correspond to 95 % or 100 % confidence levels (depending on type of uncertainty), with normal or rectangular probability distribution, and coverage factor $k = 2$ or $\sqrt{3}$, respectively.

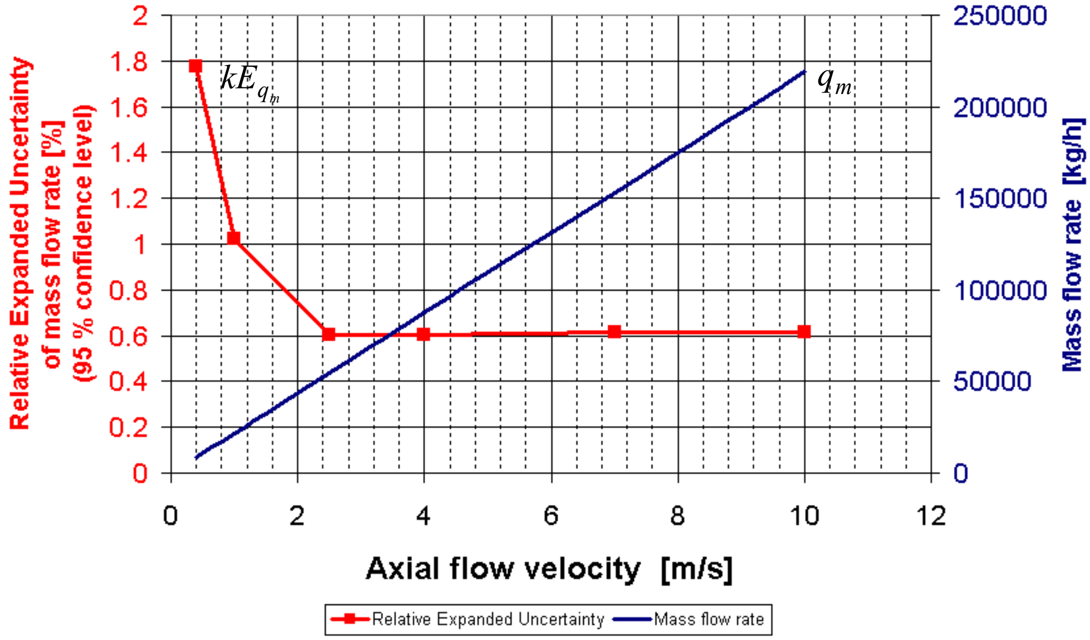

Fig. 1. Mass flow rate measurement, q_m , and its corresponding calculated relative expanded uncertainty, kE_{q_m} . The markers indicate the 6 test flow rates at which flow calibration has been made ("calibration points").

The various contributions to the relative expanded uncertainty of the mass flow rate measurement may be investigated in further detail at each of the M = 6 "calibration points" shown by markers in Fig. 1. The bar-chart shown in Fig. 2 gives the relative importance of such contributions at a flow velocity of 1 m/s. At this relatively low velocity the deviation factor uncertainty (due to the flow calibration) dominates the uncertainty budget in this example. At higher flow velocities this influence decreases (not shown here).

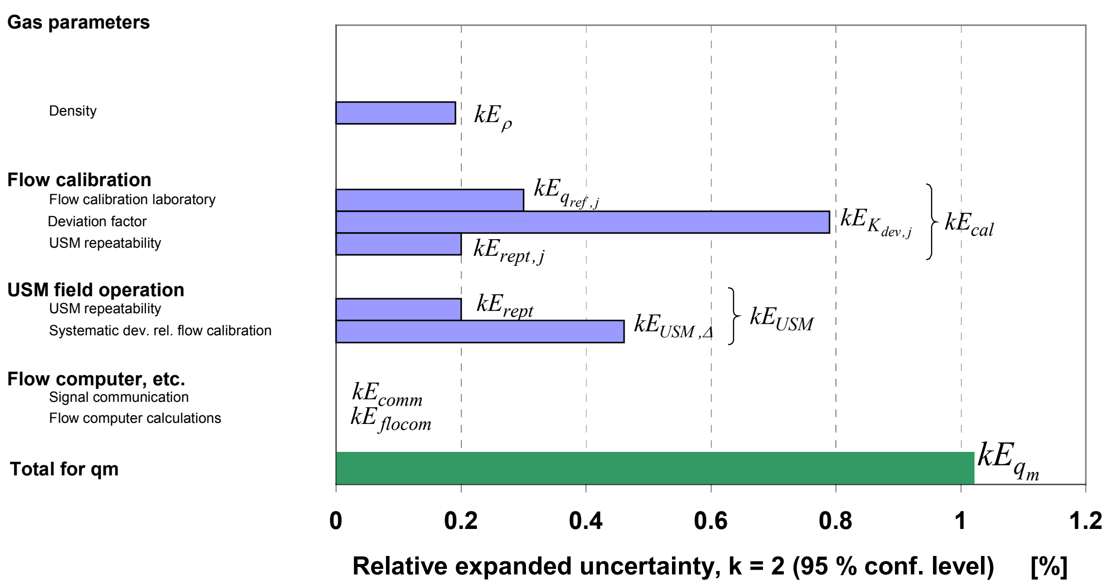

Fig. 2. Bar-chart showing contributions to the calculated relative expanded uncertainty of the mass flow rate measurement, at 1 m/s flow velocity.

In Fig. 2 the relative expanded uncertainty of the Solartron 7812 densitometer measurement is calculated to about 0.19 %. It may be of interest to investigate the relative importance of the various contributions to this uncertainty figure. Fig. 3 shows the contributions to the expanded uncertainty of the Solartron 7812 densitometer, calculated according to Eq. (6). It appears that the densitometer uncertainty is totally dominated by the "densitometer accuracy" $u(\hat{\rho}_u)$. Other uncertainty contributions are relatively smaller.

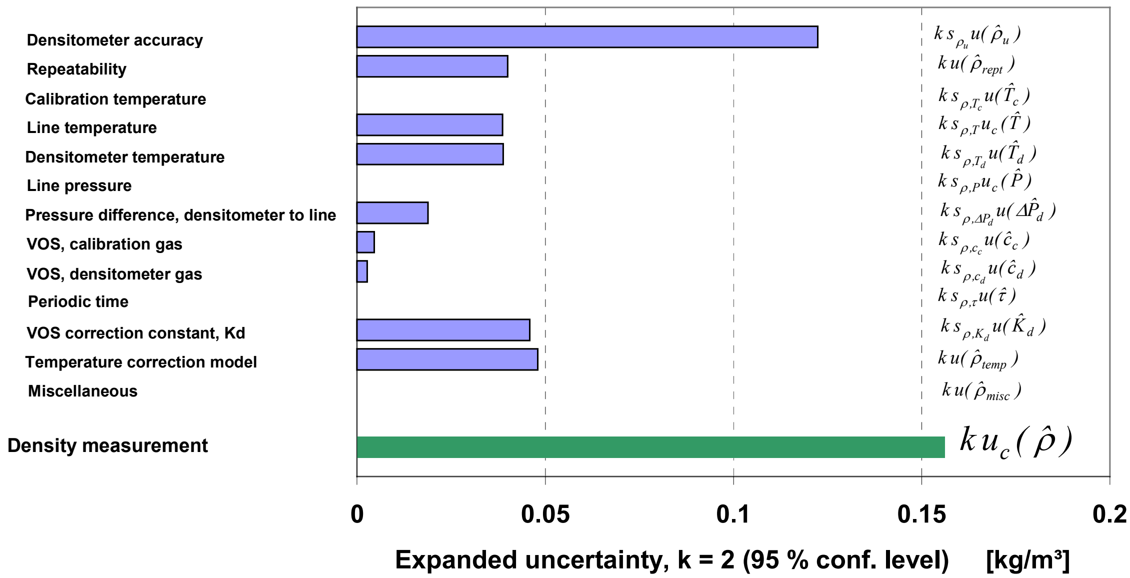

Fig. 3. Bar-chart showing the various contributions to the expanded uncertainty of the Solartron 7812 gas densitometer measurement, calculated according to Eq. (6).

To investigate the relative expanded uncertainty of the USM field measurement shown in Fig. 2 in some more detail, Fig. 4 shows shows the contributions to this uncertainty, calculated according to Eqs. (9)-(18). These are grouped into four groups: USM repeatability in field operation, meter body uncertainty, uncertainty of systematic transit time effects, and the integration method uncertainty (installation effects). In the present example all four groups contribute significantly to the USM field uncertainty. In general the latter two groups are the most difficult to specify (only the USM repeatability is available from current USM manufacturer data sheets), and tentative uncertainty figures have been used in the present calculation example, to demonstrate the sensitivity to these uncertainty contributions.

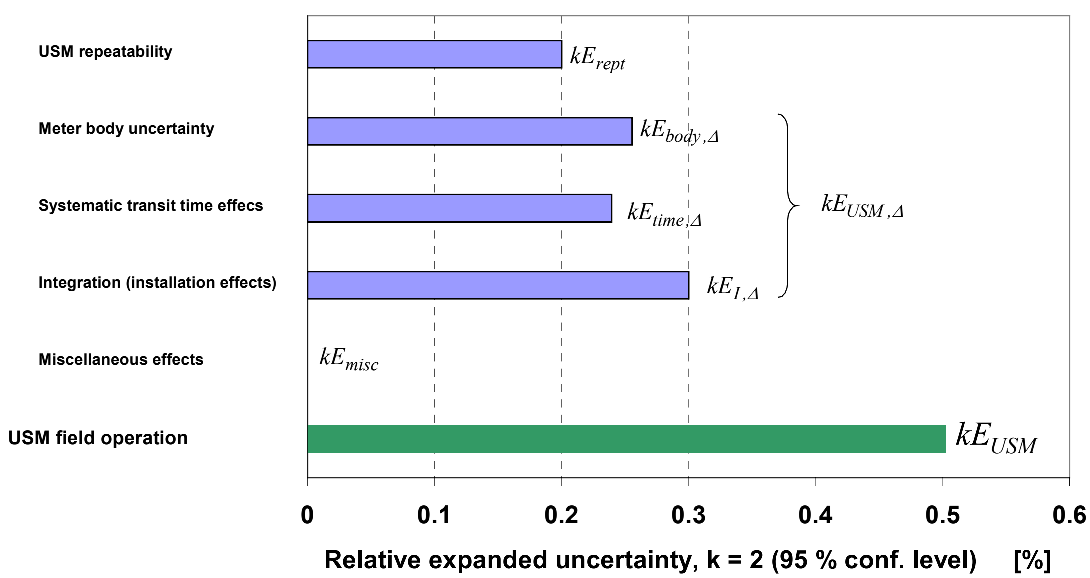

Fig. 4. Bar-chart showing the various contributions to the expanded uncertainty of the USM field measurement, at 1 m/s flow velocity, calculated according to Eqs. (9)-(18).

Table 3 summarizes the calculation results of this example in an overall uncertainty budget. Note that the relatively large calculated relative expanded mass flow rate uncertainty of the metering station at this low velocity, about 1 %, is mainly due to the deviation factor uncertainty, which contributes with almost 0.8 %, cf. Fig. 2. It would be possible to reduce this uncertainty contribution significantly by using another correction factor, *K*, and thus reducing the overall uncertainty of the station. However, here the AGA-9 [6] example for the deviation factor is used as a convenient case, where *K* has been calculated on basis of the flow-weighted mean error, FWME (i.e. single-factor correction, with constant *K* over the flow rate range). Note that at higher flow velocities the relative expanded uncertainty is lower, cf. Fig. 1.

Table 3. Uncertainty budget for the USM fiscal gas metering station example, for the mass flow rate, q_m, calculated according to Eq. (2), for a flow velocity of 1 m/s.

Source	Uncertainty contribution				Combined uncertainty	
	Relative expanded uncertainty	Confidence level & probab. distribution	Cover. factor, *k*	Relative standard uncertainty	Rel. sens. coeff.	Relative Variance
Density measurement, ρ	0.19 %	95 % (normal)	2	0.095 %	1	$9.025 \cdot 10^{-7}$
Flow calibration	0.87 %	95 % (normal)	2	0.434 %	1	$1.88 \cdot 10^{-5}$
USM field operation	0.50	95 % (normal)	2	0.25 %	1	$6.32 \cdot 10^{-6}$
Signal comm. & flow computer	Neglected	-	-	-	1	0
Sum of relative variances				$E_{q_m}^2$		$2.602 \cdot 10^{-5}$
Relative combined standard uncertainty				E_{q_m}		0.510 %
Relative expanded uncertainty (95 % confidence level, k = 2)				$k \cdot E_{q_m}$		**1.02 %**

The uncertainty evaluation example discussed above, for the mass flow rate q_m, does not involve conversion to standard reference conditions using the *P*, *T* measurements and the *Z*-factor calculations. However, similar analyses can be made for *Q* and q_e, involving the *P*, *T* measurements and *Z*-factor calculations. Similar bar-charts may then be calculated e.g. for the pressure transmitter, the temperature element/transmitter, the *Z*-factor calculations, the USM flow calibration, etc. For documentation purposes, necessary reporting of input data and calculated results is available, for the four measurands given by Eq. (1).

6 CONCLUSIONS

In the NPD regulations it is stated that "it shall be possible to document the total uncertainty of the measurement system. An uncertainty analysis shall be prepared for the measurement system within a 95 % confidence level" [4]. The *GUM* [2] put requirements to such documentation. The expanded uncertainties calculated by the program *EMU - USM Fiscal Gas Metering Station* may be used in such documentation of the metering station uncertainty. That means, provided the user of the program (on basis of manufacturer information or another source) can document the numbers used for the input uncertainties to the program, the *Handbook* and the program gives procedures for propagation of these input uncertainties.

For traceability purposes the inputs to the program (quantities and uncertainties) must be documented by the user. The user must also document that the calculation procedures and functional relationships implemented in the program are in conformity with the ones actually applied in the fiscal gas metering station[9].

In this context there may be a need for improved information on USM uncertainties provided in current USM manufacturer data sheets. Two numbers are normally available [8-10]: "accuracy" and repeatability. The "accuracy" is usually not defined, which may cause confusion with respect to what type of uncertainty the "accuracy" accounts for, for the meter at hand (e.g. systematic transit time effects, installation effects, etc.). Moreover, information on its possible variation with pressure, temperature, installation conditions and deviation from flow calibration to field operation, is generally lacking. The repeatability is often not specified as a function of flow velocity (or flow rate), which may be a simplification. Normally a single repeatability figure is given, and it should be specified whether this figure accounts for flow calibration, field operation, or both. Confidence levels and probability distributions are lacking (both for "accu

[9] If the "overall level" options of the program are used, the program should cover a wide range of situations met in practice.

racy" and repeatability), causing problems with converting the specified numbers to standard uncertainties, which are needed to calculate the uncertainty of the metering station. A discussion is given in [1].

The uncertainty model for USM fiscal gas metering stations presented in the *Handbook* is based on present-day "state of the art of knowledge" for stations of this type, and is not expected to be complete with respect to description of effects influencing on such metering stations. In spite of that, the uncertainty model does account for a large number of the important factors that influence on the expanded uncertainty of metering stations of this type. It is expected that the most important uncertainty contributions have been accounted for. Evaluation of the effects of these factors on the uncertainty of the metering station should be possible with the uncertainty model and the program developed here.
It is the intention and hope of the partners presenting this *Handbook* that - after a period of practical use of the *Handbook* and the program - the uncertainty model presented here will be subject to necessary comments and viewpoints from users and developers of USMs, and others with interest in this field, as a basis for a possible later revision of the *Handbook*. The overall objective of such a process would of course be that - in the end - a useful and accepted method for calculation of the uncertainty of USM fiscal gas metering stations can be agreed on, in the Norwegian metering society as well as internationally.

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