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Gas quality parameters where gas composition cannot be measured online

Eivind Nag Mosland, NORCE Norwegian Research Centre AS
Camilla Sætre, University of Bergen and NORCE AS
Kjell-Eivind Frøysa, Western Norway University of Applied Sciences and NORCE AS

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1 INTRODUCTION

At metering stations for custody transfer of natural gas, gas quality parameters such as molar mass, density at line and reference conditions and calorific value are found by calculations based on gas composition as measured by an online gas chromatograph. In metering stations upstream the custody transfer point it may not be cost-efficient to install gas chromatographs (GCs). In such situations, alternative means for determination of quality parameters must be considered. Furthermore, for possible future subsea custody transfer metering stations, use of gas chromatographs may not be technically possible. Finally, back-up solutions for a gas chromatograph can be beneficial, in particular for un-manned platforms.

In addition to flow velocity, ultrasonic transit time flow meters (USMs) measure velocity of sound (VOS) on each acoustic path. These measurements are used for health check of the flow meter applying two different approaches: 1) inter-comparison of velocity of sound measured on different acoustic paths, and 2) comparison of measured velocity of sound with velocity of sound calculated from measured gas composition. Several efforts have been made on correlating the measured velocity of sound to the quality parameters of natural gas. This paper addresses a recent development of such an algorithm that is more robust with respect to the variety of real gas compositions. It is tested on real cases from offshore installations and land terminals, covering a wide range of pressure and temperature. This indicates that use of measured velocity of sound can be a realistic alternative for determination of natural gas quality parameters in situations where gas chromatographs or other analyzers are not feasible from an economical or a technical point of view.

2 BACKGROUND AND METHODOLOGY

2.1 Background and basic principles

The algorithm presented in this work follows a similar approach as that described in the NSFMW papers from 2005 and 2006 by Frøysa et al. [1][2], whose principles originate in work started in the 90's. It exploits the relationship between velocity of sound and density, shown in Figure 1 for a binary methane-ethane gas mixture at 65 bara and 5 °C. The velocity of sound measured by the USM is combined with the measured pressure and temperature, and gas composition assumptions to estimate relevant gas quality parameters. This relationship seems simple based on Figure 1, if prior knowledge can be used to determine if the density should be e.g.

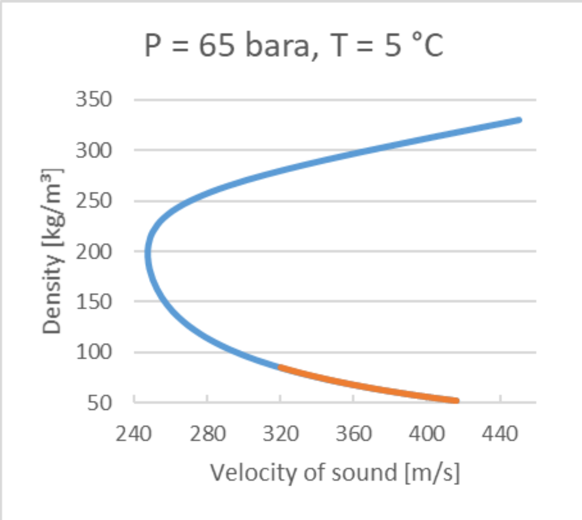

Fig. 1 – Speed of sound and density for a binary C1-C2 mixture, calculated in accordance with [3][4]. Orange part of the line covers molar mass up to 21 g/mol.

66 kg/m³ or 300 kg/m³. However, introducing the inert component nitrogen (N_2) and carbon dioxide (CO_2), and higher order hydrocarbons transforms the unambiguous line to a cloud of possible solutions. Its spread will depend on the pressure and temperature. An example is shown in Figure 2 for gas mixtures with molar mass up to approximately 21 g/mol at 155 bara and 55 °C. The blue graph shows results for hydrocarbon mixtures without N_2 or CO_2, while the orange graph shows results for similar hydrocarbon mixtures, but with 2 mol% N_2 and 2 mol% CO_2. The hydrocarbon mixtures contain alkanes from C1 to nC6. For a single VOS in the example below, a gas containing CO_2 or N_2 will have a higher density than for a gas of only hydrocarbons. It can also be shown that a gas with more higher order hydrocarbons will in general have a lower density than a binary C1-C2 mixtures at the same VOS. Note that complexity increases for heavier gases, close to and past the turning point shown in Figure 1.

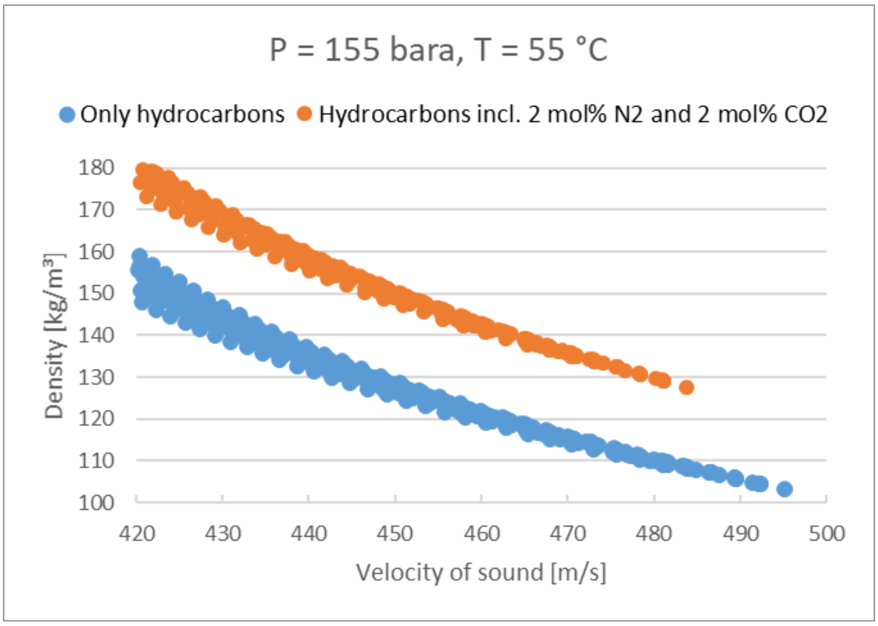

Fig. 2 – Possible combinations of speed of sound and density for different natural gas mixtures with molar mass up to approximately 21 g/mol calculated in accordance with [3][4].

Due to these challenges, dubbed "the uniqueness problem", "the effects of higher order hydrocarbons (C3+)" and "the effects of inert gas components" in [1], assumptions about the natural gas composition and/or additional input parameters are needed to obtain a solution. The approach used in the present work is presented in Section 2.2 below. For a more thorough description of the history of the method, as well as an overview of other proposed methods for indirect estimation of gas quality parameters, the reader is referred to [1].

2.2 Methodology

The algorithm used in this work, takes measured velocity of sound, pressure, temperature and a typical gas composition as input. When implemented at a metering station, the input values of VOS, pressure and temperature are updated live with data from the USM, and pressure and temperature transmitters. The typical gas composition is an approximate "best guess" gas composition which is updated at regular or irregular intervals, e.g. weekly, monthly, annually, depending on uncertainty requirements and expected variability of the composition. This typical gas composition can be based on historic data, process simulations, sampling or other sources. Accurate input estimates for the N_2 and CO_2 molar fractions are more important than for the hydrocarbons. In this way, the online VOS-measurement will in principle account for all deviations between the pre-defined typical gas composition and the actual gas composition.

Using the typical composition as a starting point, small changes in the gas composition are made following a set of assumptions detailed below which through an iterative procedure yields an equivalent gas composition, matching the measured VOS at the input pressure and temperature. This is in turn used to calculate the estimated gas parameters; Gross Calorific Value (GCV) at 25 °C reference combustion temperature (unit MJ/kg) and line density (unit kg/m³).

The full set of input parameters to the method are:

- Measured velocity of sound, *VOS*
- Measured line pressure, *P*
- Measured line temperature, *T*
- Estimated typical molar fraction (mol%) of nitrogen, N_2
- Estimated typical molar fraction (mol%) of carbon dioxide, CO_2
- Estimated typical molar fraction (mol%) of methane, *C1*
- Estimated typical molar fraction (mol%) of ethane, *C2*
- Estimated typical molar fraction (mol%) of propane, *C3*
- Estimated typical molar fraction (mol%) of iso-butane, *iC4*
- Estimated typical molar fraction (mol%) of normal-butane, *nC4*
- Estimated typical molar fraction (mol%) of iso-pentane, *iC5*
- Estimated typical molar fraction (mol%) of normal-pentane, *nC5*
- Estimated typical molar fraction (mol%) of hexanes and higher, *C6+*

The main difference between the present algorithm and the algorithms presented in [1] and [2] is the use of a more detailed typical gas composition, with input molar fractions up to C6+, while the "Typical composition approach" (TCA) in [1][2] is limited to C3+. Although this adds complexity to the method, it has the advantage of significantly reducing model uncertainty and bias, especially when the amount of C7 and higher order hydrocarbons is negligible.

The iterative procedure exploits the relation between the molar mass of the gas mixture and the velocity of sound at the given temperature and pressure. This relation is not linear nor always with a unique solution. Therefore, a set of assumptions are required to solve the problem set forth. These assumptions are:

- There are only negligible amounts of gas components other than those listed as input parameters present in the gas mixture
- The input for molar fraction of hexanes and higher, C6+, can be approximated as normal hexane, nC6, in the calculations
- Input molar fractions of N_2 and CO_2 are known, and are therefore not to be adjusted in the iterations
- The relative amounts of hydrocarbons from C2 and upwards are constant, i.e. the ratios C2/C3, C3/iC4, iC4/nC4, nC4/iC5, iC5/nC5 and nC5/C6+ are not altered in the iterations and can thus be treated as a group

From an initial guess on the velocity of sound, calculated from the input parameters, the ratio of C1 and the group of higher order hydrocarbons is changed until the calculated VOS converge to the measured VOS and equivalent gas composition is obtained. Mass based GCV is calculated from the equivalent composition, while calculation of the line density also requires pressure and temperature. Together with the volume flow rate at line conditions measured by the USM, q_v, the mass flow rate, q_m, and energy flow rate, q_e, can be calculated by Equations (1) and (2), respectively.

$$q_m = \rho q_v \quad (1)$$

$$q_e = H_{sm} \rho q_v \quad (2)$$

Here H_{sm} is the mass based GCV and ρ the line density. The method can also be used to calculate the density at standard conditions, ρ_0, volume based GCV (MJ/Sm³) and the ratio of compressibilities, Z/Z_0, but this is not discussed here.

Calculations of line density and VOS are currently performed using the "Detailed characterization method" equations of state for natural gas in Report No. 8 (1994) [3] and report No. 10 (2003) [4] from the American Gas Association (AGA), also adopted as ISO 20765-1:2005 [5], and the international standard for calculation of calorific values of natural gas, ISO 6976:1995 [6], as they are still frequently used in the industry.

Replacing the calculation method for GCV with that described in ISO 6976:2016 [9] and for line density and VOS with that described in AGA Report No. 8 part 2 [7] will not significantly change the output or uncertainty of the estimated quantities for pressures, temperatures and natural gas mixtures in the normal range / zone 1 of the 1994 version of AGA reports No. 8 [3]. AGA Report No. 8 part 1 [7] yields same results as the preceding AGA 8 and AGA 10, but with updated validity ranges for pressure, temperature and composition. AGA Report No. 8 part 2 is identical to ISO 20765-2:2015 [8] and has an expanded uncertainty of 0.1 % also outside the pressure, temperature and composition ranges of [3].

3 FIELD TESTS

The performance of the method has been tested off-line using real data from two offshore platforms and two land terminals. Each of the land terminals have four or more parallel lines. One offshore platform has two lines in series. The other has two lines in parallel, used one at a time. Hourly spot values for up to one year have been analyzed for each case. The analyzed data contains the gas composition in normalized mole fractions for C1, C2, C3, nC4, iC4, nC5, iC5, C6+, N_2 and CO_2, as measured by an online GC. Measured pressure, temperature, flow velocity and velocity of sound are available for each line. The pressure ranges from approximately 50 to 200 bar, and the temperature from approximately 0 to 60 °C.

To simulate a real measurement situation where the gas is sampled annually, the algorithm has been given a single typical gas composition for the whole period while the input pressure, temperature and velocity of sound is updated continuously.

The algorithm's density and GCV estimates are presented for three different typical gas compositions for each installation. As the molar fractions of N_2 and CO_2 are not adjusted by the algorithm, they are the most important part of the input typical composition. The three different typical compositions are therefore chosen to be such that the sum of the molar fractions of N_2 and CO_2 is close to the average (orange), high (grey) and low (yellow). The use of the typical gas composition where the sum of the molar fractions of N_2 and CO_2 are close to average can be considered as close to a best-case scenario. The two other typical gas compositions can be considered as close to worst-case scenarios. The density and GCV estimates are compared to the "reference" calculated from the measured pressure, temperature and gas composition using AGA 8 [3], AGA 10 [4] and ISO 6976:1995 [6]. C6+ is treated as nC6 in the calculations. Data points where the flow velocity is below 0.3 m/s are not shown. The deviation from the reference is for line density given by

$$\Delta\rho = \frac{\rho_{est} - \rho_{ref}}{\rho_{ref}} \cdot 100\ \%, \qquad (3)$$

where ρ_{est} is the density output from the algorithm and ρ_{ref} is the calculated reference density. The deviation in GCV is calculated in a similar way.

In addition, the measured VOS is compared to the VOS calculated from the measured gas composition, pressure and temperature by use of AGA 10 [4]. This comparison can be used for evaluation of the condition of the USM.

It is important to keep in mind that deviations observed are not the same as the uncertainty of the methods, because of the uncertainty in the measured data and in the AGA8, AGA10 and ISO 6976 models themselves. The full uncertainty analysis including these effects is carried out in Section 4.

3.1 Land Terminal 1

Hourly data from Land Terminal 1 for the one-year period from August 2018 to August 2019 have been analyzed. The molar mass of the gas mixture ranges from 17.191 g/mol to 18.645 g/mol. The temperature ranges from 1.4 °C to 19 °C and the pressure from 54.1 to 70.0 bara. The N_2 and CO_2 molar fractions range from

0.52 % to 1.66 % and from 0.38 % to 2.70 %, respectively. The molar mass of the gas mixture and the CO_2 and N_2 molar fractions are shown in Figure 3, with the three different typical gas compositions highlighted. Measured pressure and temperature for Line 1 are shown in Figure 4. The average deviation between the measured and reference velocity of sound is -0.16 m/s, or -0.04 %. The standard deviation of this deviation between measured and reference velocity of sound is 0.28 m/s, or 0.07 %.

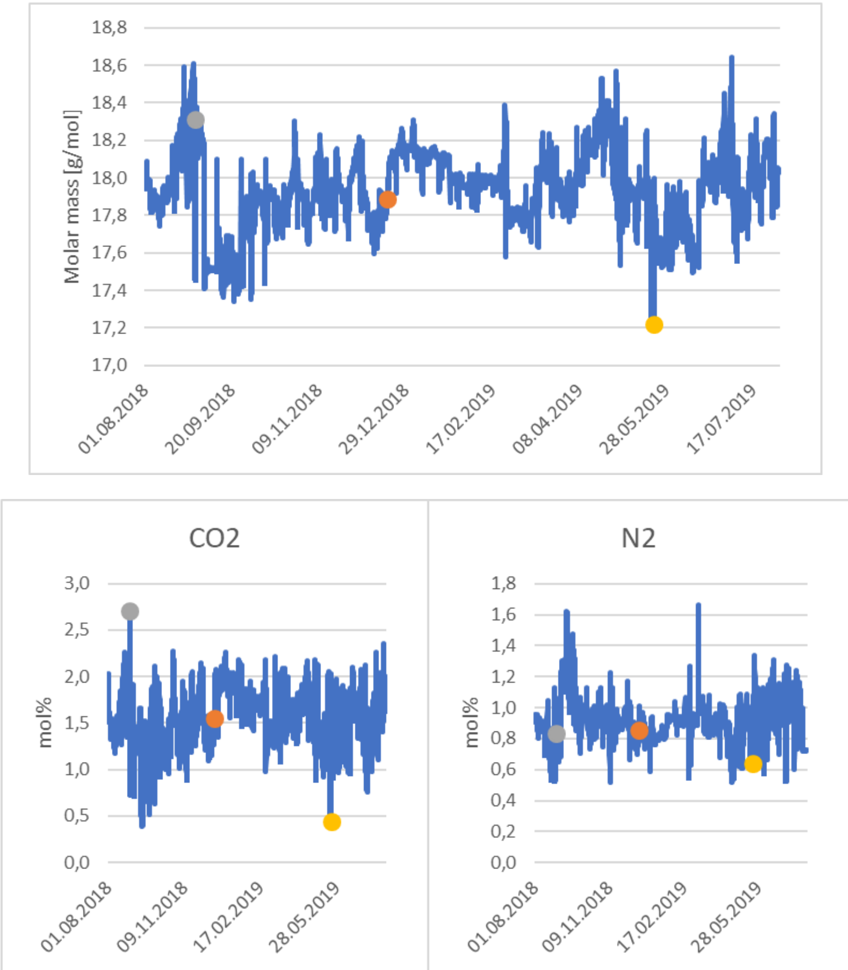

Fig. 3 – Land Terminal 1. Molar mass of the gas mixture (top) and molar fraction of CO_2 and N_2 (bottom). "Sampling points", i.e. compositions used as typical gas compositions in the algorithm, are highlighted. Orange is best-case, grey and yellow are worst-case.

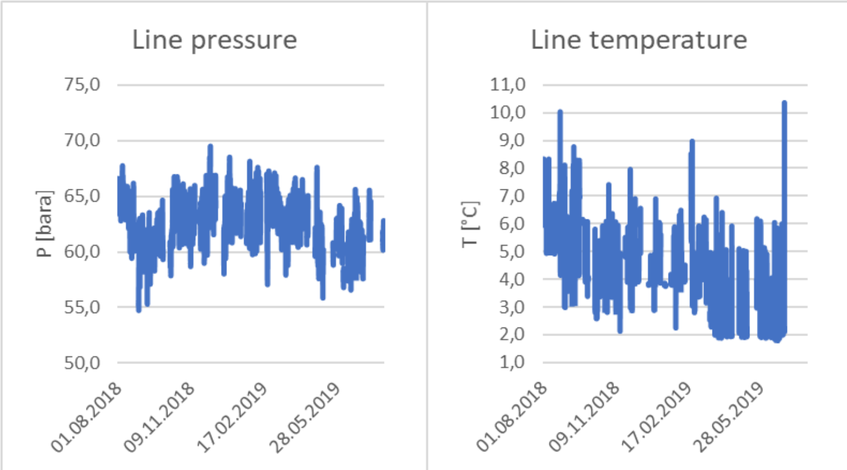

Fig. 4 – Land Terminal 1: Measured pressure and temperature in line 1 when the measured flow velocity is above 0.3 m/s.

Results for density and GCV are presented in Figure 5 for the three different typical gas compositions, in colors matching the sample points shown in Figure 3. It is seen that the deviation between estimated and reference line density is generally below 0.5 % for all three input compositions, but with a visible offset for the middle and bottom graphs. The average deviation between estimated and reference line density over the whole time period is -0.08 % (orange graph), 0.11 % (grey graph) and -0.31 % (yellow graph). The standard deviations of the spread of the data are 0.14 % (orange graph), 0.15 % (grey graph) and 0.14 % (yellow graph).

The deviation is generally higher for the GCV, but generally below 2 % for the best-case (orange graph). The average deviation between estimated and reference GCV over the whole time period is 0.11 % (orange graph, N), -2.65 % (grey graph) and 3.16 % (yellow graph). The standard deviations of the spread of the data are 0.70 % in all three graphs.

3.2 Land Terminal 2

Hourly data from Land Terminal 2 for all of 2018 have been analyzed. The molar mass of the gas mixture ranges from 17.386 g/mol to 18.207 g/mol. The temperature ranges from -3.3 °C to 9.4 °C and the pressure from 50.7 to 63.1 bara. The N_2 and CO_2 molar fractions range from 0.58 % to 1.54 % and from 0.54 % to 2.09 %, respectively. The molar mass of the gas mixture and the CO_2 and N_2 molar fractions are shown in Figure 6, with the three different typical gas compositions highlighted. Measured pressure and temperature for Line 1 are shown in Figure 7. The average deviation between the measured and reference velocity of sound is -0.05 m/s, or -0.01 %. The standard deviation of this deviation between measured and reference velocity of sound is 0.35 m/s, or 0.09 %.

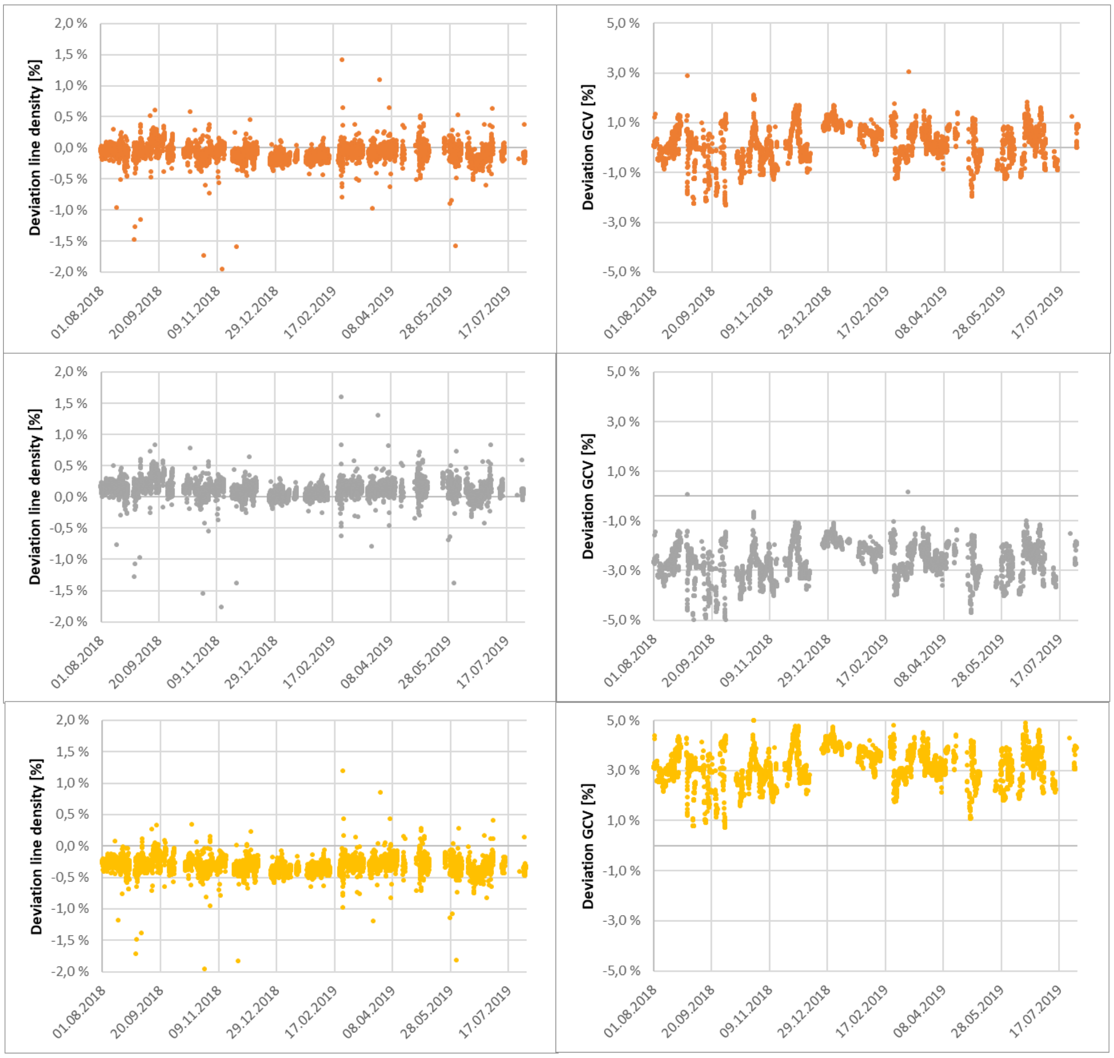

Fig. 5 – Land Terminal 1: Deviation from reference in estimated line density (left) and GCV (right) for three different typical gas compositions as indicated in Figure 3. The total molar fraction of the inert components (N_2 and CO_2) is close to the average for the top graphs, high for the middle graphs and low for the bottom graphs.

Results for density and GCV are presented in Figure 8 for the three different typical gas compositions, in colors matching the sample points shown in Figure 6. The average deviation between estimated and reference line density over the whole time period is 0.00 % (orange graph), 0.13 % (grey graph) and -0.15 % (yellow graph). The standard deviations of the spread of the data are 0.18 % in all three graphs.

The average deviation between estimated and reference GCV over the whole time period is -0.18 % (orange graph), -1.41 % (grey graph) and 1.25 % (yellow graph). The standard deviations of the spread of the data are 0.61 % in all three graphs.

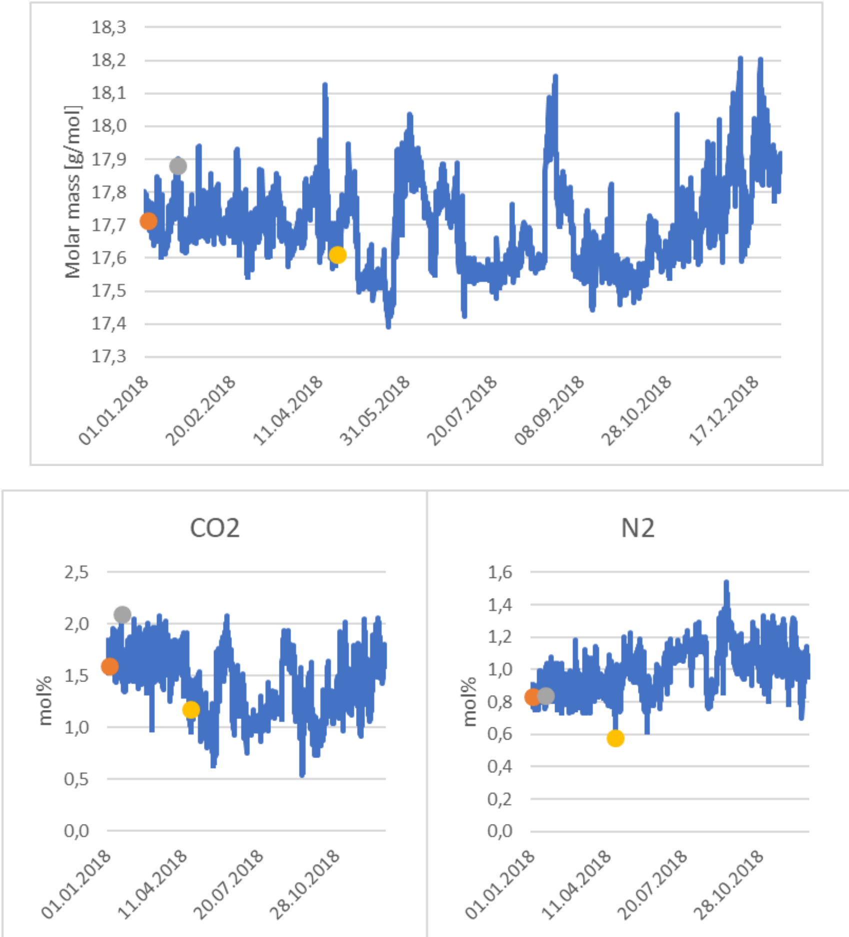

Fig. 6 – Land Terminal 2. Molar mass of the gas mixture (top) and molar fraction of CO_2 and N_2 (bottom). "Sampling points", i.e. compositions used as typical gas compositions in the algorithm, are highlighted. Orange is best-case, grey and yellow are worst-case.

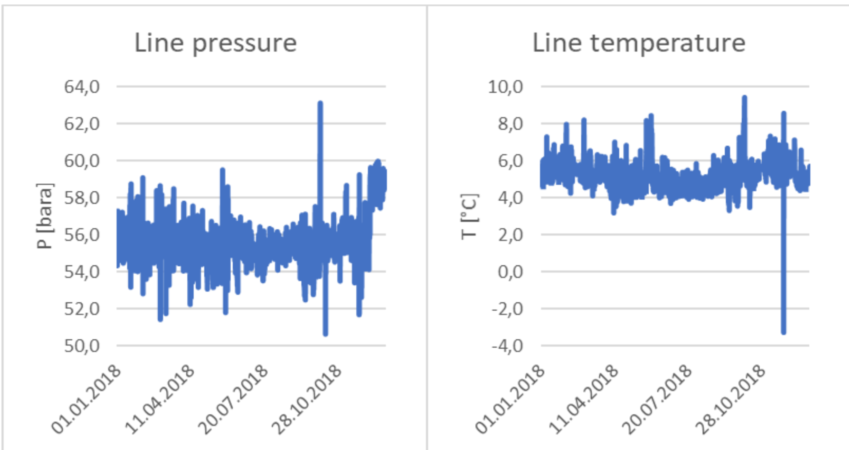

Fig. 7 – Land Terminal 2: Measured pressure and temperature in line 1 when the measured flow velocity is above 0.3 m/s.

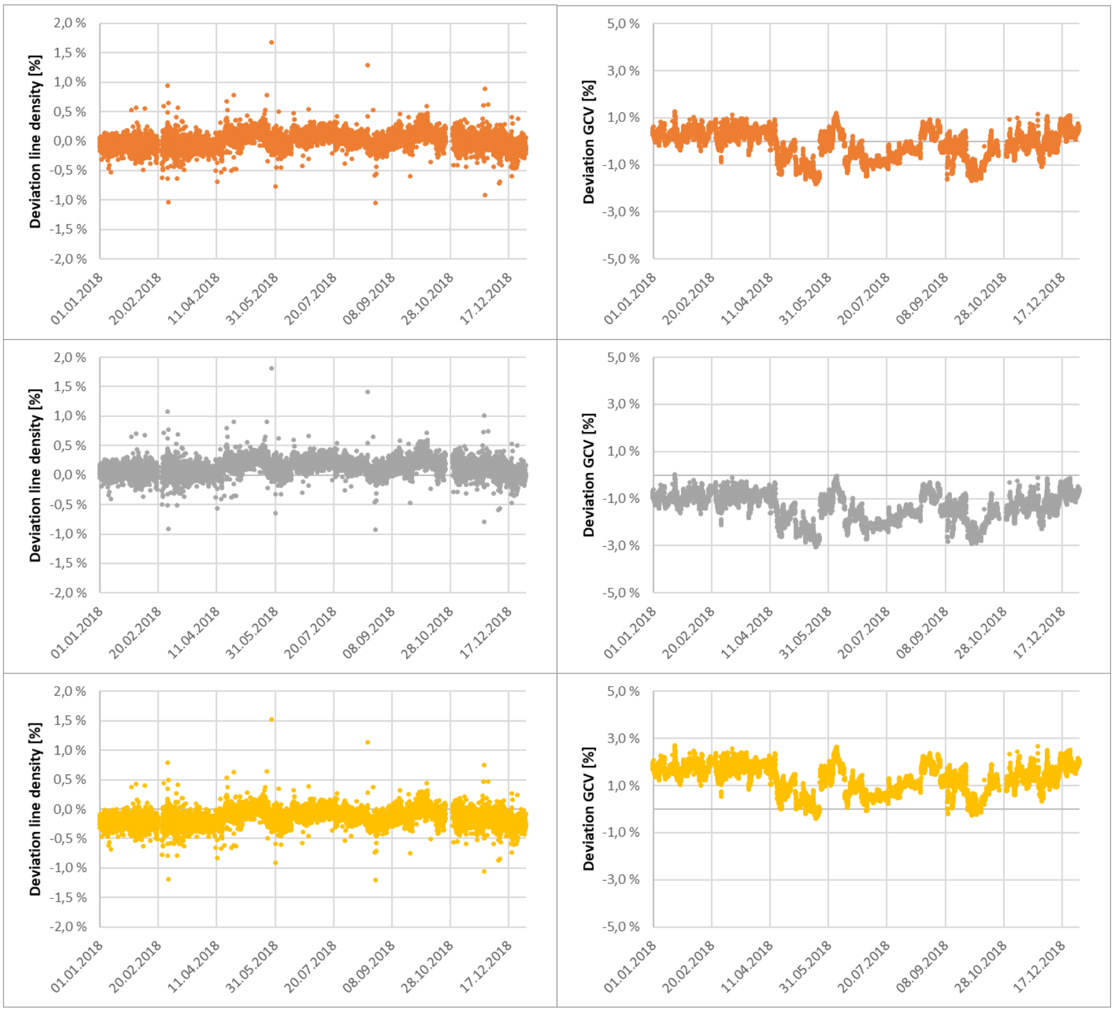

Fig. 8 – Land Terminal 2: Deviation from reference in estimated line density (left) and GCV (right) for three different input compositions as indicated in Figure 6. The total molar fraction of the inert components (N_2 and CO_2) is close to the average for the top graphs, high for the middle graphs and low for the bottom graphs.

3.3 Offshore Platform 1

Hourly data from Offshore Platform 1 from June 1, 2018 to May 1, 2019 have been analyzed. The molar mass of the gas mixture ranges from 18.932 g/mol to 20.123 g/mol. The temperature ranges from 40.4 °C to 60.0 °C and the pressure from 141 to 192 bara. The N_2 and CO_2 molar fractions range from 0.58 % to 1.07 % and from 1.58 % to 2.46 %, respectively. The molar mass of the gas mixture and the CO_2 and N_2 molar fractions are shown in Figure 9, with the three different typical gas compositions highlighted. Measured pressure and temperature for Line 1 are shown in Figure 10. The two parallel lines at the offshore platform are not used simultaneously and results for both lines are therefore shown to cover the whole time period. Line 1 is shown in black and Line 2 in colour in the graphs. The average deviation between the measured and reference velocity of sound is -0.45 m/s, or -

0.10 % for Line 1 and 0.21 m/s or 0.05 % for Line 2. The standard deviation of this deviation between measured and reference velocity of sound is 0.63 m/s, or 0.14 % for Line 1 and 0.21 m/s, or 0.09 % for Line 2.

Results for density and GCV are presented in Figure 11 for the three different typical gas compositions, in colors matching the sample points shown in Figure 9. The average deviation between estimated and reference line density over the time period when Line 1 was in operation is -0.29 % (orange graph), -0.56 % (grey graph) and -0.13 % (yellow graph). The standard deviations of the spread of the data are 0.30 % (orange graph), 0.30 % (grey graph) and 0.31 % (yellow graph). For the time period when line 2 was in operation, the average deviation between estimated and reference line density is 0.11 % (orange graph), -0.24 % (grey graph) and 0.31 % (yellow graph). The standard deviations of the spread of the data are 0.22 % (orange graph), 0.20 % (grey graph) and 0.23 % (yellow graph).

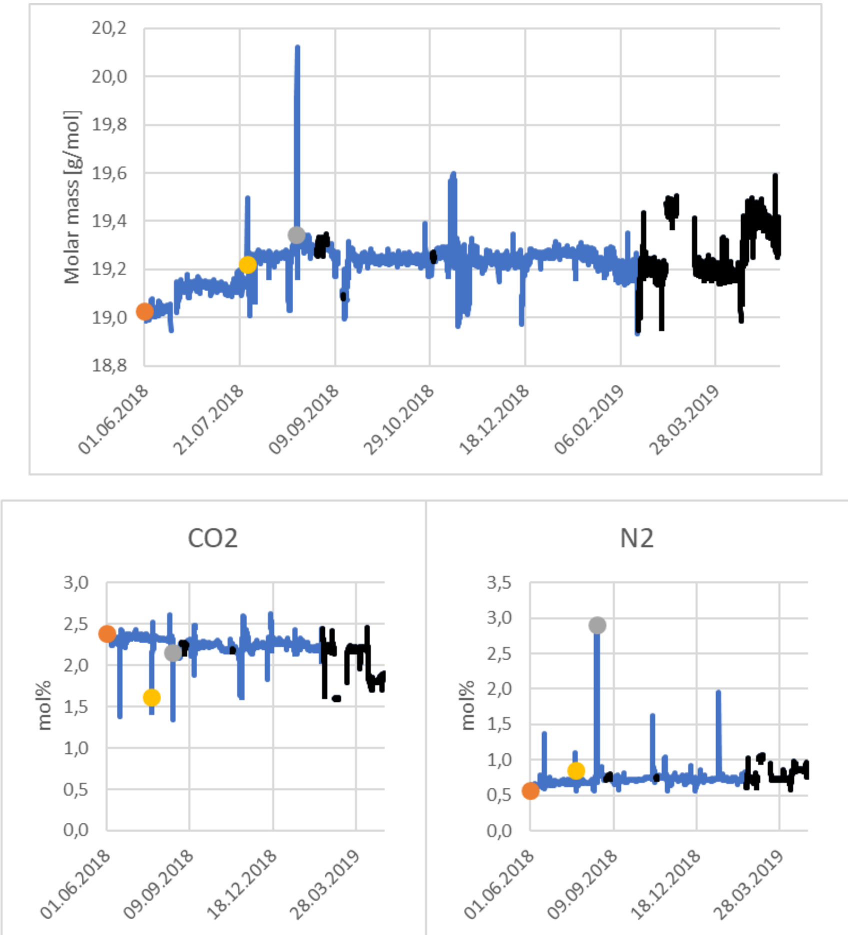

Fig. 9 – Offshore Platform 1. Molar mass of the gas mixture (top) and molar fraction of CO_2 and N_2 (bottom). "Sampling points", i.e. compositions used as typical gas compositions in the algorithm, are highlighted. Orange is best-case, grey and yellow are worst-case.

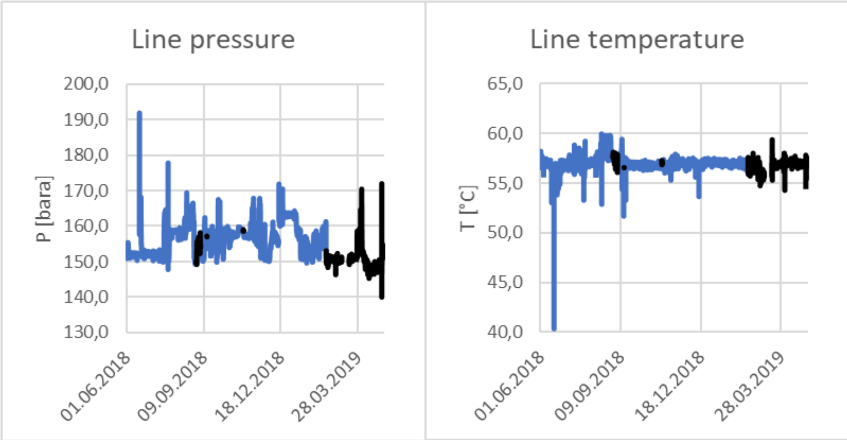

Fig. 10 – Offshore Platform 1: Measured pressure and temperature in line 1 when the measured flow velocity is above 1.0 m/s. Black part of the curves corresponds to the times when Line 1 has been in use. In rest of the time period Line 2 has been in use.

The average deviation between estimated and reference GCV over the time period when Line 1 was in operation is -0.40 % (orange graph), -3.38 % (grey graph) and -0.89 % (yellow graph). The standard deviations of the spread of the data are 0.36 % (orange graph), 0.34 % (grey graph) and 0.38 % (yellow graph). For the time period when line 2 was in operation, the average deviation between estimated and reference GCV is -0.06 % (orange graph), -3.05 % (grey graph) and 1.23 % (yellow graph). The standard deviations of the spread of the data are 0.29 % (orange graph), 0.28 % (grey graph) and 0.29 % (yellow graph).

Apart from "spikes" in the N_2 and CO_2 mole fractions, and a sharp decrease in the CO_2 content at the end of the period, the combined inert molar fraction is relatively stable, resulting in deviations in the estimates of less than 1 % if the typical input composition has been obtained in a stable period.

3.4 Offshore Platform 2

Hourly data from Offshore Platform 2 for the first 7 months of 2019 have been analyzed. The molar mass of the gas mixture ranges from 16.778 g/mol to 17.602 g/mol. The temperature ranges from 34.8 °C to 51.1 °C and the pressure from 135 to 195 bara. The N_2 and CO_2 molar fractions range from 0.91 % to 1.8 % and from 0.36 % to 0.70 %, respectively. The molar mass of the gas mixture and the CO_2 and N_2 molar fractions are shown in Figure 12, with the three different typical gas compositions highlighted. Measured pressure and temperature are shown in Figure 13. Data is only shown where the measured flow velocity is above 1 m/s. This is to avoid the transients due to frequent production stops. Some additional data points have been removed where e.g. the gas composition or measured VOS was not updated. The average deviation between the measured and reference velocity of sound is 0.05 m/s, or 0.01 %. The standard deviation of this deviation between measured and reference velocity of sound is 0.43 m/s, or 0.09 %.

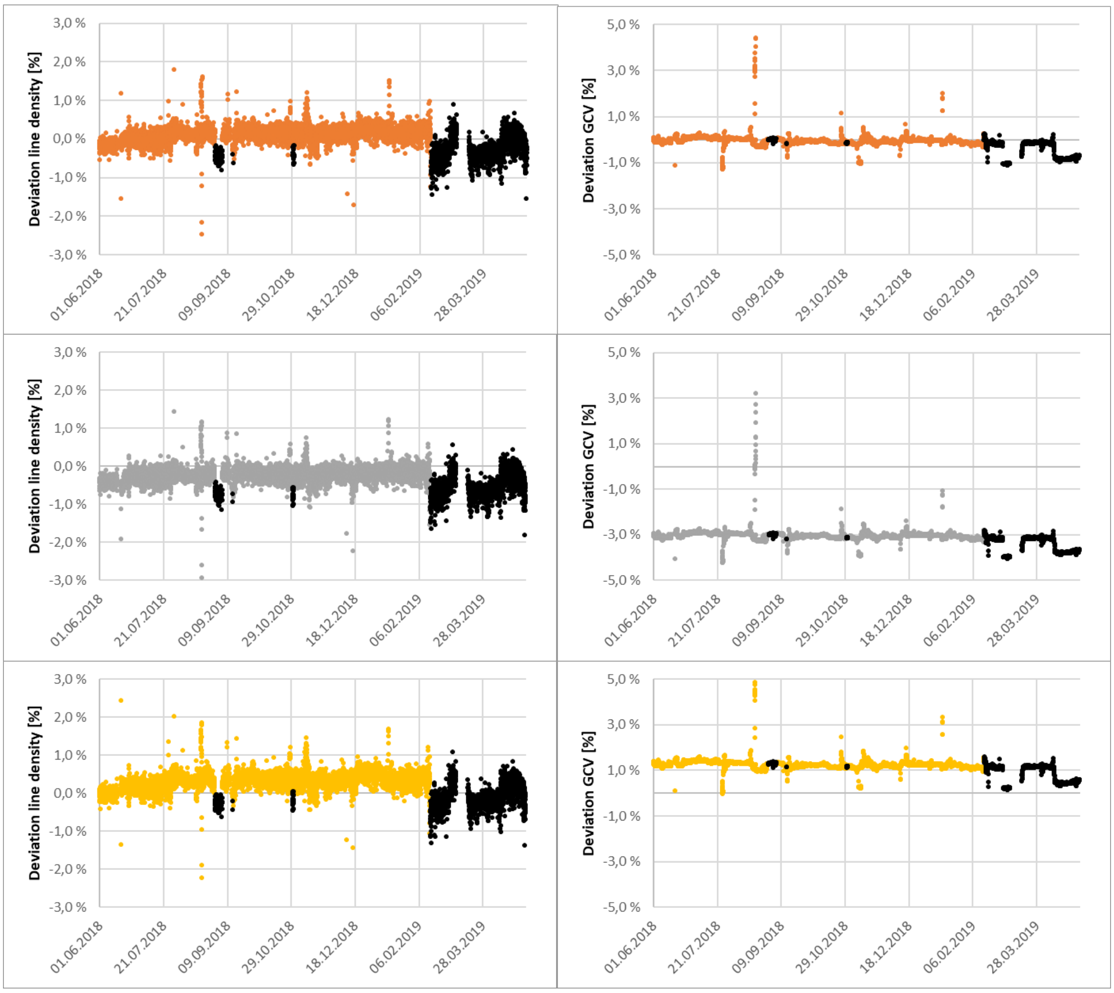

Fig. 11 – Offshore Platform 1: Deviation from reference in estimated line density (left) and GCV (right) for three different input compositions as indicated in Figure 9. Results for two meters in parallel run alternately. The total molar fraction of the inert components (N_2 and CO_2) is close to the average for the top graphs, high for the middle graphs and low for the bottom graphs. Black part of the curves corresponds to the times when Line 1 has been in use. In rest of the time period Line 2 has been in use.

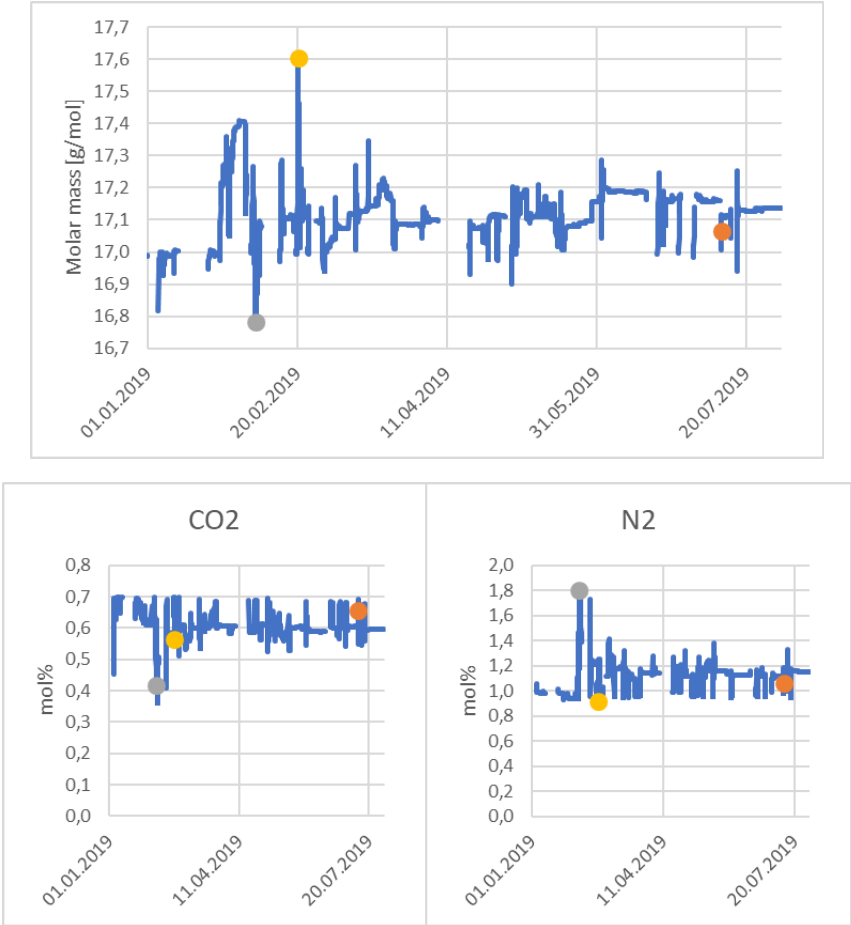

Fig. 12 – Offshore Platform 2. Molar mass of the gas mixture (top) and molar fraction of CO_2 and N_2 (bottom). "Sampling points", i.e. compositions used as typical gas compositions in the algorithm, are highlighted. Orange is best-case, grey and yellow are worst-case.

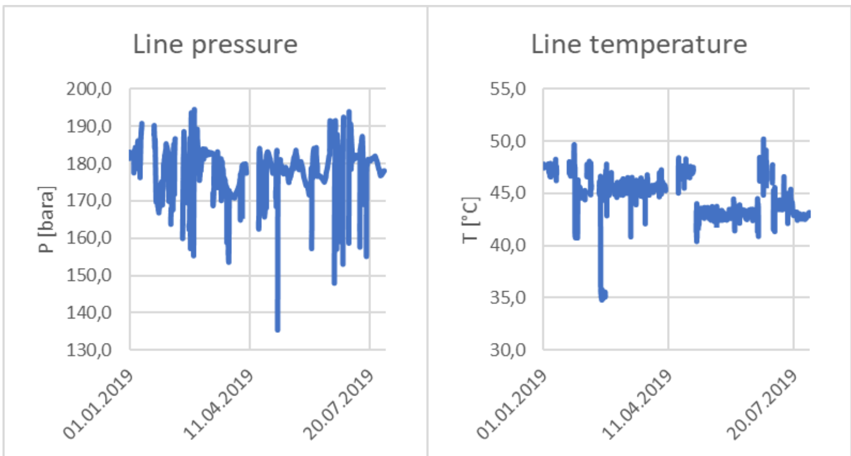

Fig. 13 – Offshore Platform 2: Measured pressure and temperature in line 1 when the measured flow velocity is above 1.0 m/s.

Results for density and GCV are presented in Figure 14 for the three different input gas compositions, in colors matching the sample points shown in Figure 12. The average deviation between estimated and reference line density over the whole time period is 0.04 % (orange graph), -0.08 % (grey graph) and 0.17 % (yellow graph). The standard deviations of the spread of the data are 0.26 % for all three graphs.

The average deviation between estimated and reference GCV over the whole time period is -0.02 % (orange graph), -0.65 % (grey graph) and 0.44 % (yellow graph). The standard deviations of the spread of the data are 0.10 % in all three graphs.

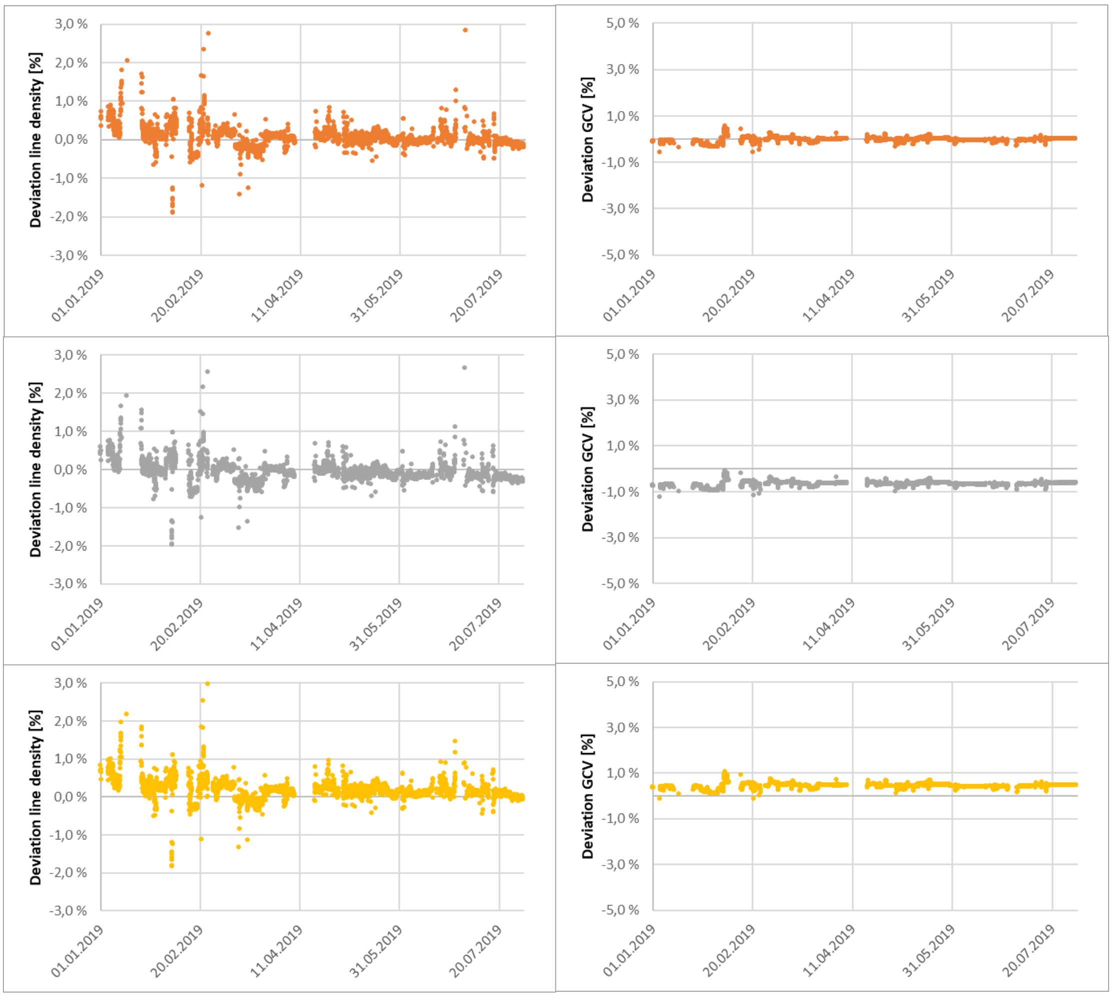

Fig. 14 – Offshore Platform 2: Deviation from reference in estimated line density (left) and GCV (right) for three different input compositions as indicated in Figure 12. The total molar fraction of the inert components (N_2 and CO_2) is close to the average for the top graphs, high for the middle graphs and low for the bottom graphs.

3.5 Summary of results

In **Table 1**, the main results from the field tests described above are summarized. For the part of the table that is related to density and GCV, the first line in the cell corresponds to results using the best-case typical gas composition (colour code orange). The two other lines corresponds to the two worst-case typical gas compositions (colour codes gray and yellow).

Table 1 – Summary of results from the field tests. The three numbers in the results related to density and GCV corresponds to the three choices of typical gas composition. Best case is shown in bold and worst case in italic.

	Land terminal 1	**Land terminal 2**	**Offshore platform 1**		**Offshore platform 2**
			Line 1	**Line 2**	
VOS, average deviation	-0.04 % (-0.16 m/s)	-0.01 % (-0.05 m/s)	-0.10 % (-0.45 m/s)	0.05 % (0.21 m/s)	0.01 % (0.05 m/s)
VOS, standard deviation	0.07 % (0.28 m/s)	0.09 % (0.35 m/s)	0.14 % (0.63 m/s)	0.09 % (0.41 m/s)	0.09 % (0.43 m/s)
N2 range	0.52-1.66 %	0.58-1.54 %	0.58-1.07 %		0.91-1.8 %
CO2 range	0.38-2.70 %	0.54-2.09 %	1.58-2.46 %		0.36-0.70 %
Density, average deviation	**-0.08 %** *0.11 %* *-0.31 %*	**0.00 %** *0.13 %* *-0.15 %*	**-0.29 %** *-0.56 %* *-0.13 %*	**0.11 %** *-0.24 %* *0.31 %*	**0.04 %** *-0.08 %* *0.17 %*
Density, standard deviation	**0.14 %** *0.15 %* *0.14 %*	**0.18 %** *0.18 %* *0.18 %*	**0.30 %** *0.30 %* *0.31 %*	**0.22 %** *0.20 %* *0.23 %*	**0.26 %** *0.26 %* *0.26 %*
GCV, average deviation	**0.11 %** *-2.65 %* *3.16 %*	**-0.18 %** *-1.41 %* *1.25 %*	**-0.40 %** *-3.38 %* *0.89 %*	**-0.06 %** *-3.05 %* *1.23 %*	**-0.02 %** *-0.65 %* *0.44 %*
GCV, standard deviation	**0.70 %** *0.70 %* *0.70 %*	**0.61 %** *0.61 %* *0.61 %*	**0.36 %** *0.34 %* *0.38 %*	**0.29 %** *0.28 %* *0.29 %*	**0.10 %** *0.10 %* *0.10 %*

4 UNCERTAINTY

The applicability of the method is mainly determined by its uncertainty, compared to regulatory requirements and the requirements of the operator. Although the above examples where the estimates have been compared with reference data clearly show the importance of good measurements of velocity of sound, and the effect of variations in gas composition, it does not fully represent the uncertainty of the method. For sales purposes, the Norwegian Measurement Regulations [11] states that the relative expanded uncertainty with 95 % confidence level of the mass flow rate should be no greater than 1.0 %. In addition, there are specific requirements for the measured variables used to calculate the flow rates, i.e. 0.3 °C for the temperature measurement, 0.3 % for the pressure measurement, 0.3 % for the measured density, and 0.3 % for the GCV.

4.1 Uncertainty model

Uncertainties for line density, mass flow rate and energy flow rate have been calculated in accordance with the Guide to the expression of uncertainty in measurement (GUM) [10] for the studied gas compositions, temperatures and pressures.

The sensitivity coefficients of the model to the different input parameters have been quantified by a numerical sensitivity analysis of the model. When calculating the uncertainty for the energy flow rate, the term $H_{sm}\rho$ in Eq. (2) is treated as one common parameter to avoid the strong correlation between the two calculated quantities. All other quantities are assumed uncorrelated.

4.2 Input uncertainties

Velocity of sound: Although a USM uses its measured VOS e.g. for quality control, it does generally not come with a stated uncertainty. However, the 2017-revision of AGA 9 Measurement of Gas Multipath Ultrasonic meters requires a comparison of measured and calculated VOS at meter calibration [12]. Based on comparison of measured values to VOS calculated from compositions from GC, temperature and pressure, it is not unrealistic to expect uncertainties in the range of 1 to 1.5 m/s for USMs predating [12]. An expanded uncertainty for measured VOS of 1 m/s is used here. The results of the field studies in Section 3 also confirm this.

Pressure and temperature: For line pressure and temperature, the uncertainty limits in [11] are used, which are 0.3 % for pressure and 0.3 °C for temperature.

Typical gas composition: The uncertainty of the input typical gas composition will depend on the application, as e.g. production from a single well will typically have less variation in composition than a comingled stream. Uncertainties could be estimated by analyzing historical data from similar cases, or by sampling at regular intervals. The uncertainties will in general increase with time if the typical composition is not updated with data from samples or simulations.

Model uncertainties: The model uncertainty of the calculation of GCV in accordance with ISO6976:1995 [6] is made up of a contribution from uncertainty in the basic data and a contribution from bias in the method. The former is less than 0.05 %, and the latter is less than 0.015 %. Assuming the contributions are uncorrelated, the total model uncertainty is less than 0.052 %.

The model uncertainty of VOS is given in **Table 2** for gas compositions in the normal range, i.e. C2 < 10 mol%, C3 < 4 mol%, C4 < 1 mol%, C5 < 0.3 mol%, C6+ < 0.2 mol%. Density is calculated by

$$\rho = \frac{P \sum \phi_i m_i}{ZRT} \quad (4)$$

where m_i and ϕ_i are the molar mass and molar fraction of each component and R is the universal gas constant, R. Assuming that the uncertainty contribution from m_i and R are negligible, the relative model uncertainty of the density equals that of the compressibility, which in turn has the same model uncertainty as the velocity of sound.

It is stated in the AGA reports [3][4] that for compositions outside the normal range, given in **Table 3**, the model uncertainty is increased. This increased uncertainty is not quantified in any way and is therefore not included in the present work.

Table 2 – Table of temperature/pressure regions and associated uncertainties of AGA8 [3] and AGA10 [4].

	Temperature Lower limit	Temperature Upper limit	Pressure Upper limit	Targeted uncertainty
Region 1	-8 °C	62 °C	120 bara	0.1 %
Region 2	-60 °C	120 °C	170 bara	0.3 %
Region 3	-130 °C	200 °C	700 bara	0.5 %
Region 4	-130 °C	200 °C	1400 bara	1.0 %

Table 3 – AGA8 and AGA10 natural gas composition molar percentage ranges, normal and extended range [3][4].

Quantity	Normal Range	Expanded Range
Mol. % Methane (C1)	45.0 to 100.0	0 to 100.0
Mol. % Ethane (C2)	0 to 10.0	0 to 100.0
Mol. % Propane (C3)	0 to 4.0	0 to 12.0
Mol. % total Butanes (C4)	0 to 1.0	0 to 6.0
Mol. % total Pentanes (C5)	0 to 0.3	0 to 4.0
Mol. % Hexanes plus (C6+)	0 to 0.2	0 to Dew Point
Mol. % Nitrogen (N_2)	0 to 50.0	0 to 100.0
Mol. % Carbon Dioxide (CO_2)	0 to 30.0	0 to 100.0

The model uncertainty of the iterative model presented here is mainly determined by the higher order hydrocarbons neglected when assuming that C6+ is only C6. This uncertainty is estimated by finding the deviation in the target quantity when comparing a calculation with only C6 and an even distribution of C6+ over nC6 to nC10. Assuming a rectangular uncertainty distribution, the standard uncertainty is found by dividing the deviation by $\sqrt{3}$.

Actual volumetric flow rate: When calculating the mass and energy flow rates, a relative expanded uncertainty with 95 % confidence level of 0.5 % is used for the USM's volume flow rate measurement at line conditions.

4.3 Examples and observations

Two example natural gas mixtures are given in **Table 4**, roughly corresponding to the gas at Land Terminal 1 and Offshore Platform 1. Their mole fractions uncertainties are estimated based on their variation over the period presented in Sections 3.1 and 3.3, respectively. Since there are not observed any clear trends in the data, it is assumed that the standard deviation can be used as an estimate of the standard uncertainty. Given these uncertainties, typical pressure and temperature for the two examples, and the input uncertainties given above, the resulting expanded uncertainty and the individual uncertainty contributors for line density and GCV are presented in Figures 15 and 16 for Land Terminal 1 and Offshore Platform 1, respectively. It is seen that the relative expanded uncertainty with 95 % confidence level of the density estimate is about 0.6 % for Land Terminal 1 and about 0.8 % for Offshore platform 1. Similar numbers for GCV are about 1.8 % for Land Terminal 1 and 1.0 % for Offshore platform 1.

Table 4 – Typical gas compositions for Offshore Platform 1 and Land terminal 1, and estimated uncertainties

Comp.	Offshore plat. [mol%]	U* [mol%]	Land terminal [mol%]	U* [mol%]
C1	86	2.5	90.7	2
C2	6.9	0.6	5.0	1
C3	2.5	0.5	1.27	0,6
iC4	0.4	0.1	0.2	0,04
nC4	0.6	0.1	0.2	0,08
iC5	0.2	0.05	0.06	0,02
nC5	0.15	0.05	0.04	0,02
C6+	0.35	0.05	0.07	0,03
N2	0.7	0.3	0.9	0,3
CO2	2.2	0.4	1.56	0,7
Molar mass	19.27 g/mol		17.92 g/mol	

The relative expanded uncertainties with 95 % confidence level of the mass flow rate and energy flow rate at Offshore Platform 1 are found to be 1.0 % and 1.5 %, respectively. For Land Terminal 1 they are found to be 0.8 % and 1.8 %, respectively. For both examples, the mass flow rate is within the NPD requirements even if the 0.3 % requirement on the line density is exceeded. In order to operate within NPD requirements, the uncertainty of both the measured VOS and pressure needs to be reduced significantly. Even for the most favorable example, Land Terminal 1, the VOS and pressure uncertainties needs to be significantly reduced, to e.g. 0.4 m/s and 0.1 % of measured pressure.

It is seen from the uncertainty budgets that the pressure and VOS measurements are the main contributors to the density uncertainty, while they are negligible for the GCV estimate. The main contributors to the GCV uncertainty are the uncertainties of the molar fractions of N_2 and CO_2. Small variations in N_2 and CO_2 have direct impact on the calorific value, since their calorific values are zero and the input molar fractions of N_2 and CO_2 are kept constant. The total hydrocarbon molar fraction is also kept constant, only changing the relative amounts of the different hydrocarbons. As such, the uncertainty in the hydrocarbon molar fractions does not have a large impact on the total calorific value.

Finally, it should be mentioned that in combinations between high pressure and low temperature, there are cases where this method cannot be used directly. This is because it then is likely that we end up in the left curve of Fig. 1, where the method is ill-posed and small uncertainties in velocity of sound can generate large uncertainties in density and GCV.

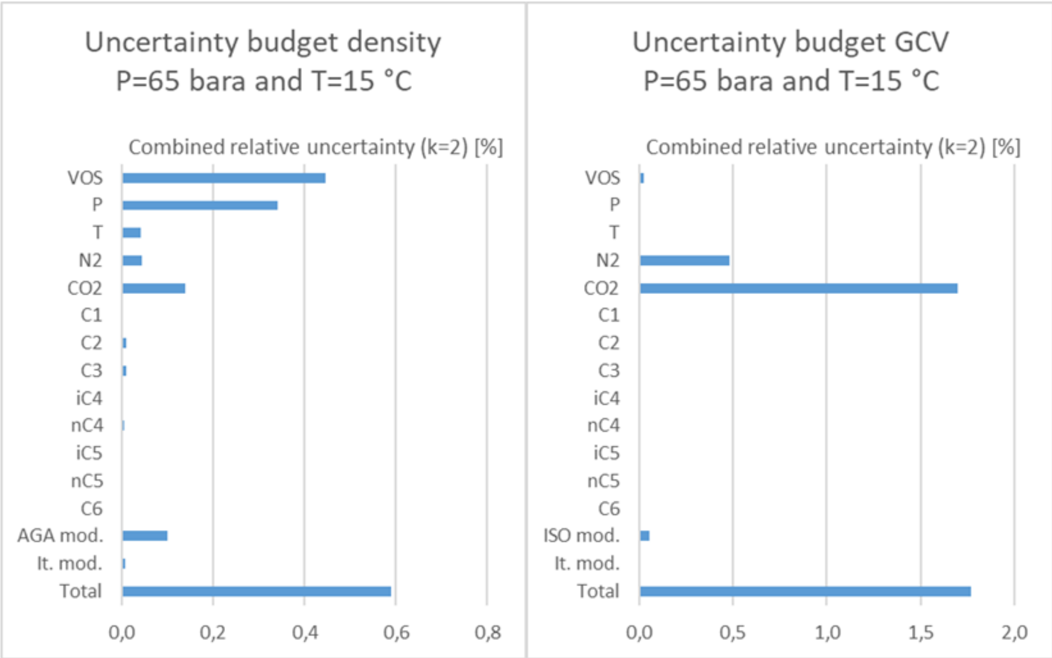

Fig. 15 – Uncertainty contributions to the relative expanded uncertainty for line density and GCV for Land Terminal 1

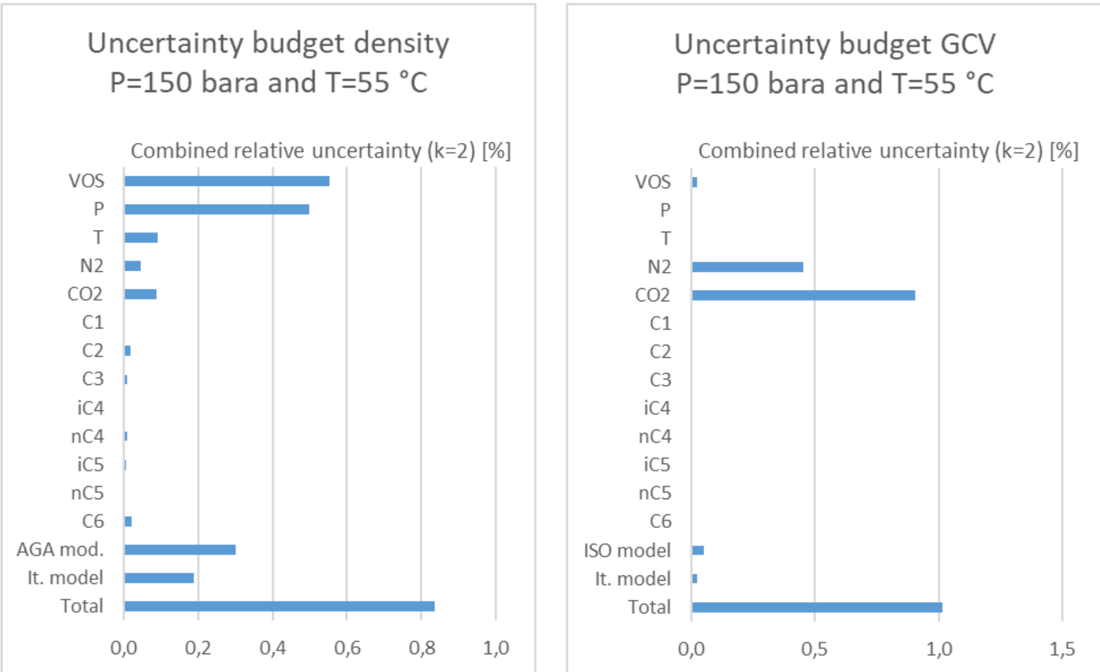

Fig. 16 – Uncertainty contributions to the relative expanded uncertainty for line density and GCV for Offshore Platform 1

5 DISCUSSION

The quality of the estimated density and GCV from the algorithm in use in this study depends on the input quantities: (i) online measured pressure, (ii) online measured temperature, (iii) online measured velocity of sound and (iv) typical gas composition (not measured online).

The online measured pressure is an important input, especially for the density estimate. In the cases considered here, it can contribute with up to 0.5 % relative expanded uncertainty in the density estimate. For the GCV estimate, the uncertainty contribution is smaller. The online measured temperature has less importance than the pressure, but it will contribute with up to about 0.1 % relative expanded uncertainty in the density estimate. The uncertainty contribution from the temperature uncertainty to the GCV estimate seems to be minimal. The pressure and temperature are according to NPD's measurement regulations to be measured online within prescribed uncertainties and with traceability to international standards. When that is done, it seems that the pressure and temperature measurements are not the critical measurements with respect to the overall uncertainty of the estimated density and GCV.

The velocity of sound is measured online by ultrasonic flow meters. The measurements of the velocity of sound are at present not traceable to international standards, and no uncertainty assessments are usually given for this measurement. However, comparisons between VOS measured by ultrasonic flow meters and VOS calculated from the online measured gas composition, pressure and temperature by use of AGA8/10, in this study showed deviations less than 1 m/s. This is also consistent with the AGA9 requirements. 1 m/s uncertainty in the velocity of sound can give a contribution of typically 0.5 % or more to the relative expanded uncertainty with 95 % confidence level for the estimated density. For estimated GCV the contribution is less. Such a contribution can clearly be seen in the results from Offshore Platform 1. There, the deviation between measured and calculated VOS was on average -0.45 m/s for line 1 and 0.21 m/s for line 2. It is seen that there is a shift in deviation of the estimated density from reference density of about -0.4 % between the times when line 1 is in operation compared to when line 2 is in operation. This can to a large extent be explained by the measured velocity of sound. For the GCV estimate, such a shift is hard to see. This is consistent with the fact that the sensitivity of the GCV to the measured VOS is much smaller than for the density.

The fixed typical gas composition is important for the accuracy of the algorithm for estimating density and GCV. As the GCV of a natural gas depends directly on the molar fractions of N_2 and CO_2 (these gases cannot burn), the GCV estimate depends more than the density estimate on the typical gas composition. The most critical part of the typical gas composition is the molar fraction of N_2 and CO_2. This can be seen when comparing the results of the field tests of the land terminals to the field tests of the offshore platforms. In the land terminals, the molar fraction of N_2 and CO_2 fluctuate more than for the offshore platforms. In long periods the molar fractions of N_2 and CO_2 at the offshore platforms are constant within 0.1 – 0.2 %. The fluctuations in deviation between the estimated GCV and the reference GCV are then smaller than similar results for the land terminals. This means that when care is taken, it should be possible to establish a typical gas composition that is representative for normal operation of an offshore field. A gas sample should be taken under normal operation, not when there are operational issues that can give unrepresentative molar fractions of N_2 and CO_2. For land terminals where the molar fractions of N_2 and CO_2 fluctuates more, a representative typical gas composition will have larger uncertainty in the molar fractions of N_2 and CO_2. Therefore larger fluctuation in the deviation between estimated and reference density is expected, and similarly for GCV.

By using the close to best-case typical gas composition, the density is estimated with an average deviation between estimated and reference density of 0.29 % or less for all the installations. When using close to worst-case typical gas compositions the average deviation is still less than 0.56 %. For Land Terminal 2 and Offshore platform 2, the average deviation is less than 0.16 % even when applying the close to worst-case typical gas composition. The standard deviation over the time period of this deviation between estimated and reference density is 0.14-0.31 %, depending on the installation. It is almost independent of what typical gas composition that is used. The uncertainty analysis valid for density estimates on a short time scale indicates a relative expanded uncertainty at 95 % confidence level of 0.6-0.8 %, depending on the field. However, the comparisons referred to above indicate that the time averaged estimated density over long time periods may be close to meet the uncertainty requirements in NPD's measurement regulation.

By using the close to best-case typical gas composition, the GCV is estimated with an average deviation between estimated and reference GCV of 0.40 % or less for all the installations. When using close to worst-case typical gas compositions the average deviation can be up to more than 3 %. The standard deviation over the time period of this deviation between estimated and reference GCV is 0.3-0.7 %, depending on the installation. It is almost independent of what typical gas composition that is used. The uncertainty analysis valid for GCV estimates on a short time scale indicates a relative expanded uncertainty at 95 % confidence level of 1.0-1.8 %, depending on the field. In order to obtain time averaged estimated GCV over long time periods that are close to meet the uncertainty requirements in NPD's measurement regulations, care must be taken that the typical gas composition represents the molar fractions of N_2 and CO_2 preferably within 0.1-0.2 %. This may be possible on many installations, but it depends on how large the variation in the molar fractions of N_2 and CO_2 is in practice.

6 SUMMARY AND CONCLUSIONS

In this study, an algorithm for estimating density and calorific value per mass unit (GCV) from measured pressure, temperature, velocity of sound and a typical fixed gas composition has been tested on field data from two land terminals and two offshore platforms. In all four cases, flow velocity and velocity of sound were measured by ultrasonic flow meters. The gas composition was measured online by gas chromatography. In addition, pressure and temperature were measured online. This means that the density and GCV could be estimated by the new algorithm. Furthermore, reference density and GCV could be established from the online gas composition, for comparisons and evaluation of the algorithm.

The density estimate showed deviations from the reference density of less than 0.3 % in most cases (averaged over long time periods). The most important issues for a precise density estimate are accurate pressure measurement and accurate velocity of sound measurements. In three out of the four installations, the deviation between measured and calculated velocity of sound was less than 0.2 m/s (averaged over long time periods). For the fourth installation, the deviation was less than 0.5 m/s. Such deviations are sufficiently small for this purpose.

The GCV estimate showed deviations from the reference GCV of less than 0.4 % in (averaged over long time periods) in cases where the typical gas composition matches well the molar fraction of N_2 and CO_2. The most important issues for a precise GCV estimate are accurate molar fractions of N_2 and CO_2 in the typical gas composition. These should be known within about 0.1-0.2 %. This can often be feasible on a production platform. On a land terminal it may be more challenging.

Uncertainty analyses for the mass flow rate are carried out for Land Terminal 1 and Offshore Platform 1. In these uncertainty analyses it is assumed that the relative expanded uncertainty at 95 % confidence level for the volumetric flow rate at line conditions as measured by the ultrasonic flow meter is 0.5 %. In this case, even if the density estimate does not quite fulfill the uncertainty requirements in the measurement regulation, the relative expanded uncertainty at 95 % confidence level for the mass flow rate is 0.8 % (Land terminal 1) and 1.0 % (Offshore Platform 1). This numbers complies with the uncertainty requirement of 1.0 % for mass flow rate in the measurement regulations.

Similar calculations are also carried out for energy flow rate. These show that the relative expanded uncertainty at 95 % confidence level for the energy flow rate is 1.5 % (Land terminal 1) and 1.8 % (Offshore Platform 1). With a careful selection of typical gas composition to be used in the algorithm for estimating density and calorific value, it is possible to reduce this uncertainty, especially at Offshore Platform 1.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

[1] FRØYSA, K.-E. and LUNDE, P. "Density and calorific value measurement in natural gas using ultrasonic flow meters", Proc. Of 23rd International North Sea Flow Measurement Workshop, Tønsberg, Norway, 18-21 October 2005.

[2] FRØYSA, K.-E., LUNDE, P., PAULSEN, A. and JACOBSEN, E. "Density and calorific value measurement in natural gas using ultrasonic flow meters", Proc. Of 24th International North Sea Flow Measurement Workshop, St. Andrews, United Kingdom, 24-27 October 2006.

[3] AGA Report No. 8: "Thermodynamic Properties of Natural Gas and Related Gases – DETAIL and GROSS Equations of State", 2nd edition, The American Gas Association, Washington DC, USA (1994)

[4] AGA Report No. 10, "Speed of Sound in Natural Gas and Other Related Hydrocarbon Gases", The American Gas Association, Washington DC, USA (2003)

[5] ISO 20765-1:2005, "Natural gas - Calculation of thermodynamic properties - Part 1: Gas phase properties for transmission and distribution applications", International Organization for Standardization, Geneva, Switzerland (2005).

[6] ISO 6976:1995, "Natural gas - Calculation of calorific value, density, relative density and Wobbe index from composition", 2nd ed. International Organization for Standardization, Geneva, Switzerland (1995).

[7] AGA Report No. 8: "Thermodynamic Properties of Natural Gas and Related Gases", 3rd edition, The American Gas Association, Washington DC, USA (2017).

[8] ISO 20765-2:2015, "Natural gas - Calculation of thermodynamic properties - Part 2: Single-phase properties (gas, liquid, and dense fluid) for extended ranges of application", International Organization for Standardization, Geneva, Switzerland (2015).

[9] ISO 6976:2016, "Natural gas - Calculation of calorific value, density, relative density and Wobbe indices from composition", 3rd ed. International Organization for Standardization, Geneva, Switzerland (2016).

[10] JCGM 100:2008: "Evaluation of measurement data — Guide to the expression of uncertainty in measurement", Bureau International des Poids et Mesures (BIPM) on behalf of the Joint Committee for Guides in Metrology, JCGM, with member organizations BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP and OIML, 2008.

[11] Norwegian Petroleum Directorate: "Regulation relating to measurement of petroleum for fiscal purposes and for calculation of CO2-tax (The Measurement Regulations", last translated 2012.

[12] AGA Report No. 9: "Measurement of Gas by Multipath Ultrasonic Meters", 3rd edition, The American Gas Association, Washington DC, USA (2017).