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Kjell-Eivind Frøysa
Christian Michelsen Research AS

Anders Hallanger
Christian Michelsen Research AS

Endre Jacobsen
Statoil ASA

Anders Løvoll Johansen
Statoil ASA

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Kjell-Eivind Frøysa, Christian Michelsen Research AS
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1 INTRODUCTION

In flare gas systems, flow measurement is important both for reports of gas emissions and for process control. Due to the nature of such systems, the flow rates in a flare line varies from very low at normal operations to full flare with very high flow rate in the case of flaring events. This means that a flow metering system for flares typically has to be able to measure flow velocities from 0.1 m/s or less, to more than 100 m/s in order to cover all cases.

The measurement of the amount of flare gas is usually carried out by an ultrasonic flare gas meter. Such meters have been in operation for several decades. They are primarily volumetric flow meters measuring the actual (line) volume flow rate of the flare gas. By calculations using the measured pressure and temperature, the volume at a selected reference condition (in Norway typically standard condition of 1.01325 bar and 15 °C) is found. Then accumulation of standard volume is carried out.

The ultrasonic flare gas meters also measure the velocity of sound in the flare gas. From the velocity of sound, pressure and temperature, the density of the flare gas can be estimated by vendor-specific algorithms. Thus, the ultrasonic flare gas meters can also provide the mass flow rate and the accumulated mass of flare gas flowing through the meter.

In the recent years, new attention has been paid to the flaring systems, due to new European regulations related to climate gas emissions [1]. For a complex system as a flare gas line, such new regulations have been challenging. The regulations have imposed new types of reports, and have to some extent suggested measurements that are at the frontier of industrial development, if not ahead. In particular this is the case for the CO_2 emission factor that is required in the new regulations. This quality factor for the flare gas has not been in focus in earlier regulations.

Such regulations have forced the industry to review their measurement systems, and evaluate how more information can be found from already existing metering stations. This is needed both in order to derive information that today is not easily measured, and in order to reduce the cost and complexity of installing new and upgraded metering stations.

In the present paper, a new and more cost-effective approach on CO_2 emission factor estimation for flare ultrasonic metering systems is presented. The approach is based on measurements already present in the flare gas metering station, in addition to some general process information for the installation in question.

In Section 2, the relevant authority requirements are presented. Thereafter, the status for flare gas metering is discussed in Section 3. This also includes possible methods for estimation of the flare gas CO_2 emission factor. In Section 4, the new method for cost-effective estimation of the CO_2 emission factor is presented. In Section 5, the uncertainty of the method is discussed, before some industrial experiences are discussed in Section 6. The conclusions are given in Section 7.

2 AUTHORITY REQUIREMENTS

The authority requirements related to climate gas emissions are focused on the two parameters (i) activity data and (ii) CO_2 emission factor.

The activity data is the annual accumulated amount of flare gas that is burnt. This can be reported either in mass or in standard volume. The expanded relative uncertainty with 95 % confidence level of the activity data shall also be documented. For large platforms, this uncertainty should be less than 7.5 %.

The CO_2 emission factor is the amount of CO_2 (mass) that is released when burning one unit of flare gas. The unit can be either a mass unit (kg) or a volume unit (Sm^3). Thus the unit of the CO_2 emission factor is either kg/kg or kg/Sm^3. Both the annual flow weighted average CO_2 emission factor, and the relative expanded uncertainty with 95 % confidence level should be reported.

3 STATUS FOR FLARE GAS METERING

In this chapter, the industrial status for estimation of activity data and CO_2 emission factor is presented.

3.1 Flow metering (activity data)

The activity data are measured by means of an ultrasonic flare gas flow meter. As discussed in the introduction, this is a volumetric flow meter. However, through the velocity of sound, such meters calculate the density and the molar mass of the flare gas. Thus, both the standard volume of flare gas and the mass of flare gas can be accumulated using such a meter. At some installations, the activity data is reported as standard volume, and at other installations activity data is reported as mass. In Norway, traditionally offshore installations have reported standard volume, and land based installations have reported mass. There is today a trend also offshore to change from standard volume to mass. This is due to uncertainty requirements on the CO_2 emission factor, and will be briefly discussed below.

3.2 CO_2 emission factor

The determination of the CO_2 emission factor for a flaring system has been a challenging task. As a starting value, a worst case factor has been used several places. This has often been selected so large that the CO_2 emission has been over-estimated. Such a factor can for example be 3.75 kg/Sm^3, close to that of ethane

A more precise CO_2 emission factor can be found by using a company specific factor. This can be based on e.g. process simulations and thus some expectations of the gas composition in the flare in question. Thus the company specific factor in many cases is more precisely called an installation specific factor.

In order to specify the CO_2 emission factor more precisely, measurements are needed. There have been several discussions related to gas composition measurements, either in form of laboratory analysis of samples of the flare gas, or by on-line gas chromatographs an the flaring line. There are, however, in general several problems with such solutions.

A gas sample can typically be taken once a week, or maybe once a day. Such a procedure is demanding with respect to man hours, laboratory use and also contains some HSE issues. Despite this, in installations where the flaring is quite constant over time, such a regime may trace the gas quality and thus the CO_2 emission factor properly, to a relative expanded uncertainty of 2.5 % with 95 % confidence level. However, in most flare gas lines, the flaring is not constant. Most of the time, there is a low flow rate, with a molar mass of the flare gas corresponding to the relevant low-flow sources, which may be continuous or of long duration. The high flaring events are shorter in duration, maybe just some minutes. However, the accumulated flow in these case may be so high as to constitute a significant part of the total

flaring over a year, a part which can be expected to have a significantly different molar mass from that the low flaring periods. This means that it will be almost impossible to obtain a representative CO_2 emission factor from gas samples, which typically will be taken during low flaring conditions.

Using an on-line gas chromatograph can possibly improve this, as a new sample is taken typically every 15 minute. However, gas composition during flaring events with a shorter time period than this, may not be measured. In addition, the flare gas is more complex than sales gas e.g. also in the sense that liquid may be present. This complicates the operation of the gas chromatographs, and thus this may not be a technically recommended solution.

In installations where the flaring is not more or less constant, there is therefore a need for new methods for cost-effective and precise estimation of the CO_2 emission factor. In the next section, such a method is proposed, based on the measurements carried out by the ultrasonic flare gas meter in addition to installation specific information.

Related to this discussion it should also be mentioned that there is a trend in the industry to change the reporting regime for fuel and flare gas from standard volume to mass. This is because the CO_2 emission factor has a much smaller change with change in gas composition when it is reported in kg/kg compared to when it is reported in kg/Sm^3. Thus, uncertainty limits are typically easier to meet for the CO_2 emission factor when it is reported in kg/kg. This is indicated in Figure 1, where the CO_2 emission factor in kg/kg and in kg/Sm^3 is plotted as a function of molar mass. The gas in this calculation consists of alkanes and a molar fraction of up to 1 % of nitrogen, carbon dioxide and water vapour respectively.

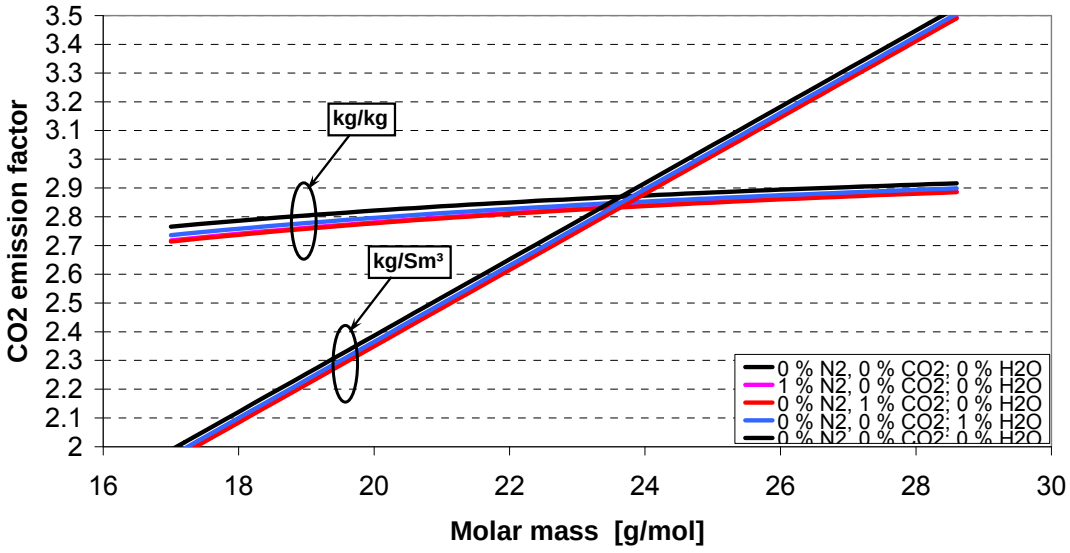

Figure 1: CO_2 emission factor as a function of molar mass, for pure alkanes, and alkanes with addition to a molar fraction of 1 % of nitrogen, carbon dioxide and water vapour, respectively.

4 NEW CO_2 EMISSION FACTOR ALGORITHM

In this chapter, the new method for estimation of the CO_2 emission factor in a cost-effective way for flaring systems is presented. The basic formulas are first derived. Thereafter there is a discussion on estimation of the inert gas content (N_2, CO_2, and H_2O) and uncertainties of such estimation.

4.1 Basic Formula

In general, the CO_2 emissions factor can be calculated from the molar fractions of each component in the flare gas, in the following way:

$$C_{C,M} = \frac{m_{CO2}}{m} \sum_{i=1}^{N} \phi_i n_i \quad (1)$$

$$C_{C,V} = C_{C,M} \rho_0 \quad (2)$$

where

$C_{C,M}$:	CO_2 emission factor, mass CO_2 per mass burnt gas
$C_{C,V}$:	CO_2 emission factor, mass CO_2 per volume (at standard pressure and temperature) burnt gas
ρ_0 :	gas density at standard pressure and temperature
m_{CO2} :	molar mass of CO_2.
m :	molar mass of the burnt gas.
ϕ_i :	molar fraction of gas component number *i* in the burnt gas.
n_i :	number of carbon atoms in the molecule of gas component number *i* in the burnt gas.
N :	total number of gas components in the burnt gas.

It has previously been considered to use knowledge about the plant, process simulation models and composition analysis of spot samples to estimate a likely average flaring composition and by that get an estimate of a fixed CO_2 emission factor. The uncertainty of such an approach would be high: A typical installation has many different sources to the flare system, with widely different compositions and thus widely different CO_2 emission factors. Since the relative contribution of each source varies over time, perhaps as much as 0 to 100%, the combined CO_2 emission factor for a flare varies widely. There is usually no metering of the individual sources and it is therefore not possible to keep track of the individual contributions to flaring. An improved method is needed, and a method has been found that utilizes the available data from the ultrasound meter. The data enables calculating the molar mass for a given period, as accumulated mass divided by accumulated moles, from which the average CO_2 emission factor for that period can be calculated.

Assuming a flare gas consisting of alkanes only, with molecular formulas CH_4, C_2H_6, C_3H_8, ..., the calculation of the CO_2 emission factor from the molar mass is exact. The general alkane formula is $C_nH_{(2n+2)}$, which is also valid for a mixture of alkanes, where *n* then becomes the average number of carbon atoms per molecule. Actually, the formula is also valid for a mixture of alkanes and hydrogen, as hydrogen (H_2) can be represented by $n = 0$ in $C_nH_{(2n+2)}$. Substituting C and H with molar masses of carbon and hydrogen (in form of single atoms and not in molecules) we get the following equation relating the molar mass, *m*, to *n* and the molar masses of carbon and hydrogen:

$$m = m_C n + m_H (2n+2) = 12.011n + 1.008(2n+2) \quad (3)$$

We are interested in finding *n*, from which the CO_2 emission factor can be calculated, and therefore we rearrange:

$$n = \frac{m - 2m_H}{m_C + 2m_H} = \frac{m - 2.016}{14.027} \quad (4)$$

We do not see pure alkane/hydrogen flare gas in practice and we therefore have to correct for the other components present, which can be unsaturated hydrocarbons as well as non-hydrocarbon inert gas components. For an offshore facility with separation of hydrocarbons, the amount of non-alkane hydrocarbons going to flare is small and thus the error from assuming that all hydrocarbons are alkanes or hydrogen is small. We do not normally see alkenes and alkynes with $n < 6$, and thus the unsaturated hydrocarbons tend to be heavy and stay in the liquid. For those that do evaporate, Eq. (4) would not give a very large error due to the dominance by mass of carbon. For example cyclo-hexane with $n = 6$, would get $n = 5.86$ by Eq. (4), while benzene would get $n = 5.43$.

The inert gas components, i.e. components that are neither hydrocarbon nor hydrogen, present in the flare gas must be corrected for. The experience from Statoil's offshore platforms is that only three inerts are present in significant amounts: Nitrogen, carbon dioxide and water. The content of these must be estimated separately by using knowledge about the plant, etc., as one would do for the hydrocarbons as well if the molar mass was not available. This means that by utilising the molar mass in the calculation of the CO_2 emission factor, one does not eliminate the uncertainty of composition estimation, but limits it to the inerts.

Eqs. (5) - (10) correct for inert mole fractions ϕ_{N2} ϕ_{CO2} and ϕ_{H2O}:

$$n = \phi_{HC} \frac{m_{HC} - 2m_H}{m_C + 2m_H} + \phi_{CO_2} \tag{5}$$

$$n = \frac{\phi_{HC} m_{HC} - 2m_H \phi_{HC}}{m_C + 2m_H} + \phi_{CO_2} \tag{6}$$

$$n = \frac{\phi_{HC} m_{HC} - 2m_H (1 - \phi_{N_2} - \phi_{CO_2} - \phi_{H_2O})}{m_C + 2m_H} + \phi_{CO_2} \tag{7}$$

The product of hydrocarbon mole fraction and molar mass, $\phi_{HC} m_{HC}$, in Eq. (7) is replaced with known values as shown in Eqs. (8) - (10).

$$m = \phi_{HC} m_{HC} + \phi_{N_2} m_{N_2} + \phi_{CO_2} m_{CO_2} + \phi_{H_2O} m_{H_2O} \tag{8}$$

$$\phi_{HC} m_{HC} = m - \phi_{N_2} m_{N_2} - \phi_{CO_2} m_{CO_2} - \phi_{H_2O} m_{H_2O} \tag{9}$$

$$n = \frac{m - \phi_{N_2} m_{N_2} - \phi_{CO_2} m_{CO_2} - \phi_{H_2O} m_{H_2O} - 2m_H (1 - \phi_{N_2} - \phi_{CO_2} - \phi_{H_2O})}{m_C + 2m_H} + \phi_{CO_2} \tag{10}$$

A CO_2 emission factor in kg CO_2 / Sm^3 gas can then be calculated from n using the molar mass of CO_2 and the molar volume of the gas at standard conditions:

$$C_{C,V} = \frac{m_{CO_2}}{V_{mol}} n \tag{11}$$

Similarly, a CO_2 emission factor in kg CO_2/kg gas can be calculated by Eq. (10):

$$C_{C,M} = \frac{m_{CO_2}}{m} n \tag{12}$$

In order to summarize, the CO_2 emission factor can be written in the following way under the assumption that the gas contains only hydrogen, alkanes, nitrogen, carbon dioxide and water vapour:

$$C_{C,M} = \frac{m_{CO2}}{m}\left(\frac{m-\phi_{N2}m_{N2}-\phi_{CO2}m_{CO2}-\phi_{H2O}m_{H2O}-2m_H\left(1-\phi_{N2}-\phi_{CO2}-\phi_{H2O}\right)}{m_C+2m_H}+\phi_{CO2}\right) \quad (13)$$

$$C_{C,V} = \frac{m_{CO2}}{V_{mol}}\left(\frac{m-\phi_{N2}m_{N2}-\phi_{CO2}m_{CO2}-\phi_{H2O}m_{H2O}-2m_H\left(1-\phi_{N2}-\phi_{CO2}-\phi_{H2O}\right)}{m_C+2m_H}+\phi_{CO2}\right) \quad (14)$$

where

m_{N2}:	molar mass of nitrogen, N_2
m_{CO2}:	molar mass of carbon dioxide, CO_2
m_{H2O}:	molar mass of water vapour, H_2O
m_H:	molar mass of hydrogen (just one atom), H
ϕ_{N2}:	molar fraction of nitrogen, N_2
ϕ_{CO2}:	molar fraction of carbon dioxide, CO_2
ϕ_{H2O}:	molar fraction of water vapour, H_2O
V_{mol}:	the molar volume

This means that the CO_2 emission factor can be found if the following input is known:

- molar mass of the flare gas
- molar fraction of nitrogen
- molar fraction of carbon dioxide
- molar fraction of water vapour

The ultrasonic flare gas meter is in principle a volumetric flow meter. Thus it accumulates standard volume of flare gas. In addition, the mass of flare gas can also be accumulated due to flare gas density estimates (from the velocity of sound). In the present algorithm, the accumulated standard volume and mass is used for calculation of an average flare gas molar mass.

The determination of the inert gas molar fractions (nitrogen, carbon dioxide and water vapour) will be addressed below.

4.2 Sources of Flare Gas

In order to address the determination of the molar fractions of the inert gas components (nitrogen, carbon dioxide and water vapour), installation specific information needs to be considered.

The flare gas in a specific installation may origin from several places in the process, including e.g.:

- Export gas
- First stage separator
- Second stage separator
- Compressor
- etc

The gas composition can be quite different for the gas from the various flare gas sources. If, for each of these flare gas sources, the molar mass and the molar fraction of nitrogen, carbon dioxide and water vapour is known either precisely or approximately.

In many cases the inert content will have some dependence on the molar mass of the flare gas. The model therefore requires that two sets of inert mole fractions are specified; one for a low molar mass and one for a high molar mass. Linear interpolation between the two is then used to find the set of inert mole fractions to be used together with the molar mass given by the ultrasound meter:

$$\phi_{N2} = \frac{m - m_{light}}{m_{heavy} - m_{light}} \phi_{heavy,N2} + \left[1 - \frac{m - m_{light}}{m_{heavy} - m_{light}}\right] \phi_{light,N2}$$

$$\phi_{CO2} = \frac{m - m_{light}}{m_{heavy} - m_{light}} \phi_{heavy,CO2} + \left[1 - \frac{m - m_{light}}{m_{heavy} - m_{light}}\right] \phi_{light,CO2} \quad (15)$$

$$\phi_{H2O} = \frac{m - m_{light}}{m_{heavy} - m_{light}} \phi_{heavy,H2O} + \left[1 - \frac{m - m_{light}}{m_{heavy} - m_{light}}\right] \phi_{light,H2O}$$

The nitrogen content tends to be high in low-molar mass gas, and low in high molar mass gas. The reason is that in a separation train most of the N_2 will go with the gas in the first stage separator. The gas from the first stage separator will have a high methane fraction and therefore a low molar mass, while gas from further separation stages will have heavier hydrocarbons and therefore a higher molar mass, and at the same time a lower N_2 fraction.

The water fraction will follow an opposite trend, as water vapour pressure divided by total pressure will be larger in the gas from the third stage separator than in the gas from the first. CO_2 does not have such clear-cut trend so it is mainly N_2 and H_2O that justify specifying two sets of inert mole fractions.

There may be cases where there is one or more sources to flare with a very high non-hydrocarbon content. If the amounts and compositions of these can be well estimated, one may be able to reduce the uncertainty by subtracting the inert part of these from the activity data before entering into the model.

Purge gas consisting mainly of nitrogen is usually metered separately, and can therefore easily be subtracted from the activity data.

Produced water degassing may also be a candidate for subtraction from the activity data, as long as only the inert part of it is subtracted. It does not follow the trend of increasing water vapour content with increasing molar mass valid for flare gas from the separation train, and linear interpolation between the two reference inert fraction sets based on flaring from the separation train will underestimate the water content. The methane part of the hydrocarbons bubbling out of the water is high, and the low total pressure combined with a fairly high temperature will give a large water vapour content even though the molar mass is low.

Subtraction of produced water degassing is less straightforward than for purge gas, because it is usually not metered directly, and because part of the water vapour can condense and drop out in the flare knock out drum.

In place of metering one can often assume the amount of gas from the water to be proportional to the amount of produced water, which is usually metered, and establish a factor, for example a gas water ratio GWR. The GWR depends on the amount of dissolved gas (determined by the conditions in the upstream vessels from which the water comes),

mostly light hydrocarbons, and the temperature, pressure and salinity, which dictate the water vapour fraction and how much of the dissolved gas is released. Process simulation software might be one way of estimating the GWR, but the common equations of state like SRK and PR with the classic mixing rules will not work, and a more advanced method is needed. For example, PVTsim with the Huron Vidal mixing rule can be used to estimate the GWR. The uncertainty must be expected to be significantly higher than one would expect for HC-HC flash calculations for which the common equations of state like SRK and PR are well suited. In addition to the rather high uncertainty of calculation, there is uncertainty due to varying pressure and temperature in the produced water degassing drum and in the vessels upstream feeding water to the degassing drum.

Before subtracting the inerts in the produced water degassing from the activity data, one should take into account condensation of water vapour in the knock out drum, which can be estimated using a process simulator. The amount of condensation in the knock out drum depends on the amount, temperature and water vapour content of other simultaneous sources, and is therefore uncertain.

As the above discussion shows, produced water degassing can introduce a large uncertainty. This uncertainty depends on how large a fraction of the total flaring the produced water degassing amounts to.

In case of a flare gas recovery system, the continuous produced water degassing will normally be recovered and returned to the process, and will only go to flare if there are upsets that send more gas to the flare than the recovery system has capacity for. In this case the produced water may constitute only a small fraction of the flaring and thus not give a large uncertainty.

If the plant has separate high and low-pressure flares, the produced water degassing will normally go the LP flare. If the produced water degassing makes up most or all of this flaring, it would be better not to subtract, and rather use its content of inerts as one of the two inert sets in the model.

If the sources to flare are normally so high in water vapour content that water will drop out in the knock-out drum, this must be taken into account when determining the sets of inert mole fractions to be entered into the model. The water vapour content is then given by the equilibrium water vapour pressure at the temperature measured at the ultrasound meter, which should be close to the temperature of the knock out drum. For large flare rates the pressure may be higher than atmospheric due to pressure drop in the stack, which should also be taken into account.

4.3 Summary of Algorithm

The proposed algorithm for calculation of the CO_2 emission factor can now be summarized in the following way:

- Measure gas volumetric flow rate and calculate molar mass in flare gas meter. The calculations depend on measured sound speed and measured temperature.
- Calculate standard volumetric flow rate by using measured pressure and temperature
- Calculate standard density from molar mass, standard pressure and standard temperature
- Calculate mass flow rate from standard density and standard volumetric flow rate
- Accumulate mass and standard volume
- Calculate average standard density from accumulated mass and accumulated volume
- Calculate average molar mass
- Calculate average mole fractions of N_2, CO_2 and H_2O from average molar mass and a heavy and light flare gas (both specified with molar mass and molar fractions of nitrogen, carbon dioxide and water vapour).
- Calculate average CO_2 emission factors, based on volume and/or mass.

5 UNCERTAINTY

5.1 Uncertainty Model

In the authority reporting of the climate gas emissions related to the burning of flare gas, also the uncertainty of the CO_2 emission factor needs to be addressed. In principle the CO_2 emission factor is calculated from the following four inputs:

- molar mass
- molar fraction of nitrogen
- molar fraction of carbon dioxide
- molar fraction of water vapour

The following uncertainty contributions will contribute to the overall uncertainty of the CO_2 emission factor estimate for the flare gas:

- Uncertainty in estimated molar mass from flare gas meter
  - Measured velocity of sound
  - Temperature measurement
  - Pressure measurement
  - Effect of accumulation
  - Model uncertainty
- Uncertainty in molar fractions N_2, CO_2 and H_2O
  - Effect from heavy and light gas simplification
  - Effect from uncertainty in molar mass
- Model uncertainty CO_2 emission factor
  - Non-ideal gases (Z-factor)
  - Non-alkanes

With the different terms as given above, the overall uncertainty model for the CO_2 emission factor can be written on relative form as

$$\left(\frac{u(C_C)}{C_C}\right)^2 = \left(\left(\frac{\partial C_C}{\partial m} + \frac{\partial C_C}{\partial \phi_{N2}}\frac{\partial \phi_{N2}}{\partial m} + \frac{\partial C_C}{\partial \phi_{CO2}}\frac{\partial \phi_{CO2}}{\partial m} + \frac{\partial C_C}{\partial \phi_{H2O}}\frac{\partial \phi_{H2O}}{\partial m}\right)\frac{m}{C_C}\frac{u(m)}{m}\right)^2 + \left(\frac{\partial C_C}{\partial \phi_{N2}}\frac{1}{C_C}u(\phi_{N2})\right)^2 + \left(\frac{\partial C_C}{\partial \phi_{CO2}}\frac{1}{C_C}u(\phi_{CO2})\right)^2 + \left(\frac{\partial C_C}{\partial \phi_{H2O}}\frac{1}{C_C}u(\phi_{H2O})\right)^2 + \left(\frac{u(C_{C,model})}{C_C}\right)^2 \quad (16)$$

Here, C_C means either $C_{C,V}$ or $C_{C,M}$, i.e. the volume based and the mass based CO_2 emission factor. It should be commented that the formula has been derived based on the functional relationship in Eqs. (14), (13) and Eq. (15). The uncertainty contributions to the estimated molar fractions of the three inert gas components are thus covered through the uncertainty of the molar mass, as this is the basic parameter for that estimation. The uncertainty contributions related to the assumption of the flare gas as a mixture of a light and a heavy flare gas is covered by the three terms addressing the uncertainty of each of these three molar fractions.

The partial derivatives can be found from Eqs. (13) , (14) and (15):

$$
\begin{aligned}
\frac{\partial C_{C,V}}{\partial m} &= \frac{m_{CO2}}{m}\left(\frac{1}{m_C + 2m_H}\right) \\
\frac{\partial C_{C,V}}{\partial \phi_{N2}} &= \frac{m_{CO2}}{V_{mol}}\left(\frac{-m_{N2} + 2m_H}{m_c + 2m_H}\right) \\
\frac{\partial C_{C,V}}{\partial \phi_{CO2}} &= \frac{m_{CO2}}{V_{mol}}\left(\frac{-m_{CO2} + 2m_H}{m_c + 2m_H} + 1\right) \\
\frac{\partial C_{C,V}}{\partial \phi_{H2O}} &= \frac{m_{CO2}}{V_{mol}}\left(\frac{-m_{H2O} + 2m_H}{m_c + 2m_H}\right) \\
\frac{\partial C_{C,M}}{\partial m} &= -\frac{C_{C,M}}{m} + \frac{m_{CO2}}{m}\left(\frac{1}{m_C + 2m_H}\right) \\
\frac{\partial C_{C,M}}{\partial \phi_{N2}} &= \frac{m_{CO2}}{m}\left(\frac{-m_{N2} + 2m_H}{m_c + 2m_H}\right) \\
\frac{\partial C_{C,M}}{\partial \phi_{CO2}} &= \frac{m_{CO2}}{m}\left(\frac{-m_{CO2} + 2m_H}{m_c + 2m_H} + 1\right) \\
\frac{\partial C_{C,M}}{\partial \phi_{H2O}} &= \frac{m_{CO2}}{m}\left(\frac{-m_{H2O} + 2m_H}{m_c + 2m_H}\right) \\
\frac{\partial \phi_{N2}}{\partial m} &= \frac{\phi_{heavy,N2} - \phi_{light,N2}}{m_{heavy} - m_{light}} \\
\frac{\partial \phi_{CO2}}{\partial m} &= \frac{\phi_{heavy,CO2} - \phi_{light,CO2}}{m_{heavy} - m_{light}} \\
\frac{\partial \phi_{H2O}}{\partial m} &= \frac{\phi_{heavy,H2O} - \phi_{light,H2O}}{m_{heavy} - m_{light}}
\end{aligned}
\tag{17}
$$

5.2 Uncertainty in Molar Mass

The first term on the right hand side of (3.2) gives the relative uncertainty contribution from the molar mass. The following uncertainty contributions are in principle identified with respect to the molar mass:

- Uncertainty in measured velocity of sound
- Uncertainty in temperature measurement
- Uncertainty if pressure measurement
- Uncertainty related to accumulation and assumption of light and heavy flare gas
- Uncertainty related to uncertainty in model for calculation of molar mass from velocity of sound

These uncertainty contributions are discussed below. It is found that the uncertainty contribution related to the uncertainty of the pressure measurement is negligible [2]. Thus, the following uncertainty model can be established for the molar mass:

$$\left(\frac{u(m)}{m}\right)^2 = \left(\frac{u(m_{VOS})}{m}\right)^2 + \left(\frac{u(m_T)}{m}\right)^2 + \left(\frac{u(m_{acc,\mathrm{mod}})}{m}\right)^2 \tag{18}$$

Uncertainty in measured velocity of sound: The molar mass of the flare gas is by the flare gas meter determined from the measured velocity of sound. Due to the low pressure, the flare gas is not far from an ideal gas. By applying the velocity of sound in an ideal gas, the following expression is found:

$$\left(\frac{u(m_{VOS})}{m}\right)^2 = \left(\frac{\partial m}{\partial c}\frac{c}{m}\frac{u(c)}{c}\right)^2 = \left(2\frac{u(c)}{c}\right)^2 \tag{19}$$

Uncertainty in temperature measurement: The uncertainty contribution of the molar mass due to uncertainty of the temperature measurement can be found from the ideal gas law as follows:

$$\left(\frac{u(m_T)}{m}\right)^2 = \left(\frac{\partial m}{\partial T}\frac{T}{m}\frac{u(T)}{T}\right)^2 = \left(\frac{u(T)}{T}\right)^2 \tag{20}$$

Uncertainty related to accumulation and assumption of light and heavy flare gas: In the application addressed in this paper, it is assumed that the flare gas consists of a heavy and a light flare gas contribution. The uncertainty component related to accumulation under this assumption this can be shown to be:

$$\begin{aligned}\frac{u(m_{acc})}{m} = &\left(\frac{m_{light}}{m}\right)\left(\frac{m_{heavy}-m}{m_{heavy}-m_{light}}\right)\left(\frac{u(m_{light,\mathrm{mod}})}{m_{light}}\right) \\ &+\left(\frac{m_{heavy}}{m}\right)\left(\frac{m-m_{light}}{m_{heavy}-m_{light}}\right)\left(\frac{u(m_{heavy,\mathrm{mod}})}{m_{heavy}}\right)\end{aligned} \tag{21}$$

It has been shown that other effects of accumulation are negligible, see [2].

Uncertainty related to uncertainty in model for calculation of molar mass from velocity of sound: The algorithm for calculation of the molar mass from the measured velocity of sound is meter specific. Due to confidential issues, the specific algorithms will not be given. Neither will the conclusions on the actual size of the uncertainty be given here. However, expressions to be used for Fluenta and GE ultrasonic flare gas meters have been given in [2]. It should be mentioned that it is possible to extend the method to also cover other vendors of ultrasonic flare gas meters.

5.3 Uncertainty in Molar Fractions of N_2, CO_2 and H_2O

The second line on the right hand side of (3.2) gives the relative uncertainty contribution from the molar fractions of N_2, CO_2 and H_2O. The following uncertainty contributions are in principle identified with respect to these molar fractions:

- Effect from uncertainty in molar mass
- Effect from heavy and light gas simplification

The first of these uncertainty contributions is covered in Section 5.2.

The effect from the heavy and light gas simplification is covered here.

The molar fractions of N_2, CO_2 and H_2O are determined by use of Eq. (15). The specified molar fractions of N_2, CO_2 and H_2O for the light and the heavy gas are thus interpolated. If there are other gas compositions that do not match this interpolation, an uncertainty contribution will occur. This is illustrated in Figure 2, where an example of a light gas with molar fraction of 22.79 g/mol and a nitrogen molar fraction of 0.9549 % is used together with a heavy gas with a molar fraction of 48.94 g/mol and a nitrogen molar fraction of 0.0331 %. The pink line then illustrates the molar fraction of nitrogen as a function of molar mass, as calculated by Eq. (15). The blue dots in the same plot indicate the gas quality that is expected to be flared from various parts of the process. The deviations between the pink line and the blue dots represents uncertainty due to molar fraction of the gas component in question (here nitrogen).

The uncertainty in the molar fraction of the inert gas components can be specified by the operator. However, a recommended value for the uncertainty is indicated based on up to 10 operator defined gas quality contributions to the flaring (the blue dots in Figure 2). The standard uncertainty in the molar fraction estimate is then recommended to be set to the standard deviation of the vertical difference between the blue dots and the pink line.

For CO_2 and H_2O the same procedure is followed as for nitrogen. It is assumed that H_2O is in its gaseous phase. If condensation is expected to take place in the flare drum, this must be corrected for.

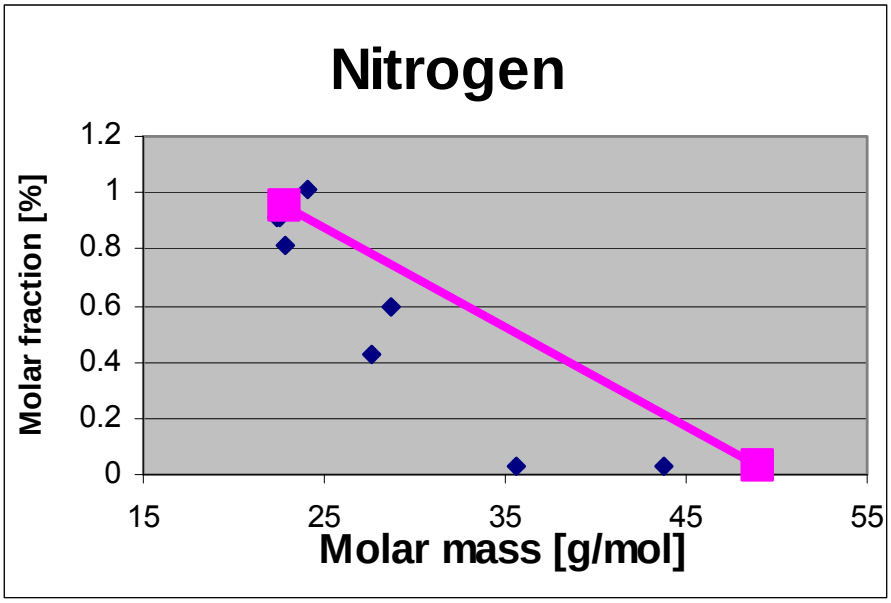

Figure 2: Interpolation of molar fraction of nitrogen, from a light and a heavy gas composition. Also included in the plot is molar fraction of nitrogen as a function of molar mass for 10 possible types of flare gas contributors. The example is synthetic, and generated with no specific installation in mind.

5.3 Model Uncertainty

The third line on the right hand side of (3.2) gives the relative uncertainty contribution from uncertainties in the model for calculation of the CO_2 emission factor from the molar mass and the molar fractions of N_2, CO_2 and H_2O itself (Eqs. (14) and (13)). Under the assumptions that the flare gas contains only alkanes, N_2, CO_2 and H_2O, this model is exact, except for compressibility effects (deviations from ideal gas). This effect is cancelled out in the mass based emission factor (Eq. (13)) while the relative uncertainty contribution will be the same as the relative uncertainty of the compressibility factor Z_0 at standard reference conditions, for the volumetric based CO_2 emission factor.

The compressibility factor at standard reference conditions can be shown to be mostly dependent on the molar mass for the gas components of relevance. It can be shown to be approximately equal to

$$\left(\frac{u(m_T)}{m}\right)^2 = \left(\frac{\partial m}{\partial T}\frac{T}{m}\frac{u(T)}{T}\right)^2 = \left(\frac{u(T)}{T}\right)^2 \tag{22}$$

$$Z_0 \approx 0.998 - \frac{(m-16)}{14}0.008 \tag{23}$$

By using Eq. (23), , the following expression is found for the relative standard uncertainty contribution due to model uncertainty:

$$\begin{aligned}\frac{u(C_{C,V,\text{model}})}{C_{C,V}} &= \frac{1}{\sqrt{3}}\left(0.002 + \frac{(m-16)}{14}0.008\right)\\ \frac{u(C_{C,M,\text{model}})}{C_{C,M}} &= 0\end{aligned} \tag{24}$$

This is based on the deviation from 1 for Z_0 that is taken as expanded uncertainty with rectangular probability distribution and 100 % confidence interval.

This is based on the deviation from 1 for Z_0 that is taken as expanded uncertainty with rectangular probability distribution and 100 % confidence interval.

5.4 Excel Spread Sheet

An Excel spread sheet has been developed to carry out the calculations of the CO_2 emission factor and the related uncertainty. The spread sheet has 6 sheets

- *README*
- *Gas input parameters*
- *Uncertainty*
- *Plot-uncertainty contribution*
- *Uncertainty guide*
- *Report CO_2*

In *README* a description of how to operate the spreadsheet is given; what is shown on the different sheets, which data input is necessary and where to seek assistance. The color code between input cells and calculated cells are also given.

In *Gas input parameter*s specifications like tags, years, flare gas meters and CO_2 emission factor (volume, mass) are given. Here also data for the light and heavy gas are given, and the measured accumulated flow data are given.

In *Uncertainty* the data for the uncertainties of measured temperature, measured speed of sound, H_2O; CO_2 and N_2 are given. A typical pressure and temperature value during flaring is also entered here[1].

The resulting uncertainty budget is shown in *Plot-uncertainty contribution*.

[1] These values are used in the estimation of the molar mass uncertainty.

In *Uncertainty guide* up to 10 different gases with input for molar mass and molar fractions of inert gases can be given. From the input suggested uncertainty in the inert gas molar fractions is calculated, this uncertainty is also shown in *Uncertainty* as a suggestion for the operator.

In *Report CO_2* the calculated CO_2 factor is shown and the resulting CO_2 emission for the gas rates given in *Gas input parameters*. The relative expanded uncertainty in the CO_2 factor is also given.

5.5 Calculation Example

Below, the actual Excel sheets are shown for a calculation carried out for a specific installation in Norwegian sector. The first data sheet, "Gas input parameters", is shown in Figure 3. Here, the type of flare gas meter, and the type of CO_2 emission factor (kg/kg or kg/Sm^3) is selected. Accumulated values of standard volume and mass of flare gas in 12 time periods (typically 12 months) can be specified. In addition, the light and heavy gas that the calculations assume the flare gas is a mixture of, is given.

A help for specification of the light and heavy gas can be found in the sheet "Uncertainty input guide". This is shown in Figure 4. Here, up to 10 different gases can be specified (molar mass and molar fraction of nitrogen, carbon dioxide and water vapour). These 10 gases are considered as being the typical sources of flare gas on the installation in question. In the plots at the bottom of that sheet, the molar fraction of nitrogen, carbon dioxide and water vapour, respectively, is plotted against the molar mass, for the 10 specified gases. In addition, the selected light and heavy gases, and the straight line between them, are shown. The closer to the straight line the dots representing the 10 gases are, the smaller is the uncertainty related to the estimation of the average molar fractions of nitrogen, carbon dioxide and water vapour. In addition, a recommended value for use as uncertainty related to the molar fraction of each of the three inert gas components is given.

In the sheet "Uncertainty budget", the recommended uncertainty values related to nitrogen, carbon dioxide and water vapour are found, see Figure 5. The user will have to specify the actual uncertainty values to be used related to the molar fraction of nitrogen, carbon dioxide and water vapour. This will often be the recommended value. In addition, uncertainty of the temperature measurement and the measurement of the velocity of sound must be given. In this example, expanded uncertainty with 95 % confidence level for the estimate of the temperature is taken as 0.3 °C, and for the estimate of the velocity of sound taken as 2 m/s. The basis for the uncertainty analysis in the temperature measurement is the specific routines and calculations carried out at the specific installation. For the uncertainty of the velocity of sound in a flare gas meter, not much information exists. However, based on [3], a value of 2 m/s has been selected as a typical but not low value. With this input, the sheet gives the uncertainty budget for the CO_2 emission factor. In this example, a relative expanded uncertainty with 95 % confidence level of 2.4 % is found.

In the sheet "Plot-uncertainty contributions" the various uncertainty contribution's impact on the output uncertainty (the relative expanded uncertainty of the CO_2 emission factor" is shown graphically, see Figure 6.

Finally, the sheet "Report CO_2" gives the CO_2 emission factor in addition to its relative expanded uncertainty with 95 % confidence level. Furthermore the total emission of CO_2 (mass) is given, see Figure 7.

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CO2 emission factor in flare systems, version 1.0

Gas input parameters

Specification of flaring system

Name of flaring system	Platform Alpha, HP Flare
Reporting period	2009
Type of flare gas meter	Fluenta FGM 130/160
Type of CO2 emission factor	kg CO2/Sm³

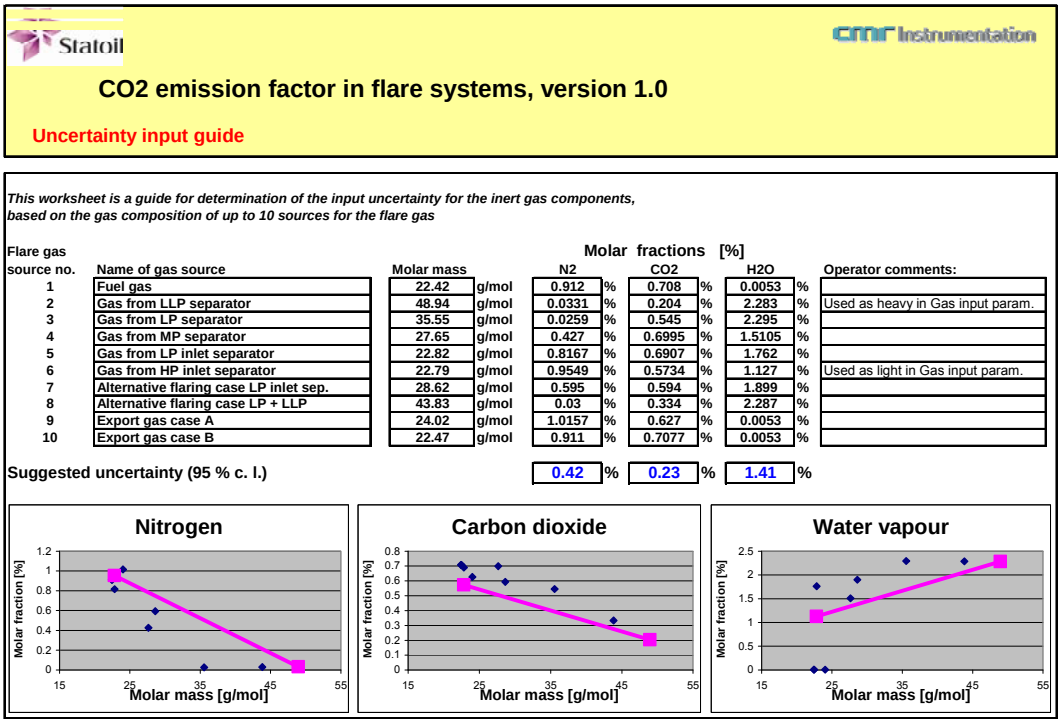
Specification of typical gas compositions

	Light gas		Heavy gas	
Molar mass	22.79	g/mole	48.94	g/mole
Molar fraction, N_2	0.9549	%	0.0331	%
Molar fraction, CO_2	0.5734	%	0.204	%
Molar fraction, H_2O	1.127	%	2.284	%

Measured flow data

Measured accumulated flare gas values	MASS		VOLUME	
Time period no. 1	417 029	kg	374 026	Sm³
Time period no. 2	1 412 388	kg	1 228 239	Sm³
Time period no. 3	604 866	kg	585 262	Sm³
Time period no. 4	304 209	kg	282 444	Sm³
Time period no. 5	524 113	kg	492 561	Sm³
Time period no. 6	748 956	kg	674 605	Sm³
Time period no. 7	1 031 172	kg	911 023	Sm³
Time period no. 8	618 694	kg	557 210	Sm³
Time period no. 9	557 122	kg	517 969	Sm³
Time period no. 10	551 857	kg	507 923	Sm³
Time period no. 11	570 280	kg	497 417	Sm³
Time period no. 12	1 099 384	kg	907 685	Sm³
Total	8 440 070	kg	7 536 365	Sm³

Figure 3: Gas input parameter sheet



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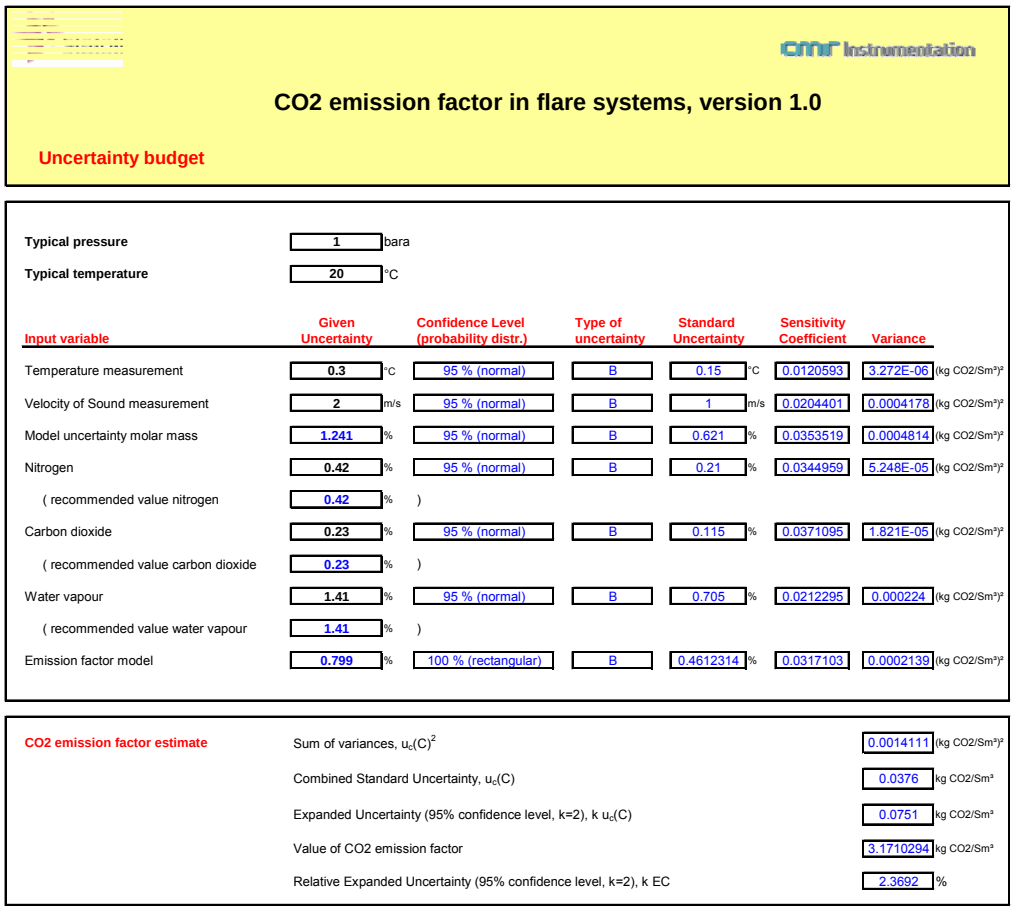
Uncertainty input guide

This worksheet is a guide for determination of the input uncertainty for the inert gas components, based on the gas composition of up to 10 sources for the flare gas

Flare gas source no.	Name of gas source	Molar mass		Molar fractions [%] N2		CO2		H2O		Operator comments:
1	Fuel gas	22.42	g/mol	0.912	%	0.708	%	0.0053	%	
2	Gas from LLP separator	48.94	g/mol	0.0331	%	0.204	%	2.283	%	Used as heavy in Gas input param.
3	Gas from LP separator	35.55	g/mol	0.0259	%	0.545	%	2.295	%	
4	Gas from MP separator	27.65	g/mol	0.427	%	0.6995	%	1.5105	%	
5	Gas from LP inlet separator	22.82	g/mol	0.8167	%	0.6907	%	1.762	%	
6	Gas from HP inlet separator	22.79	g/mol	0.9549	%	0.5734	%	1.127	%	Used as light in Gas input param.
7	Alternative flaring case LP inlet sep.	28.62	g/mol	0.595	%	0.594	%	1.899	%	
8	Alternative flaring case LP + LLP	43.83	g/mol	0.03	%	0.334	%	2.287	%	
9	Export gas case A	24.02	g/mol	1.0157	%	0.627	%	0.0053	%	
10	Export gas case B	22.47	g/mol	0.911	%	0.7077	%	0.0053	%	
Suggested uncertainty (95 % c. l.)				0.42	%	0.23	%	1.41	%	

Figure 4: Uncertainty input guide sheet



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CO2 emission factor in flare systems, version 1.0

Uncertainty budget

Typical pressure	1	bara
Typical temperature	20	°C

Input variable	Given Uncertainty		Confidence Level (probability distr.)	Type of uncertainty	Standard Uncertainty		Sensitivity Coefficient	Variance	
Temperature measurement	0.3	°C	95 % (normal)	B	0.15	°C	0.0120593	3.272E-06	(kg CO2/Sm³)²
Velocity of Sound measurement	2	m/s	95 % (normal)	B	1	m/s	0.0204401	0.0004178	(kg CO2/Sm³)²
Model uncertainty molar mass	1.241	%	95 % (normal)	B	0.621	%	0.0353519	0.0004814	(kg CO2/Sm³)²
Nitrogen	0.42	%	95 % (normal)	B	0.21	%	0.0344959	5.248E-05	(kg CO2/Sm³)²
(recommended value nitrogen	0.42	%	)						
Carbon dioxide	0.23	%	95 % (normal)	B	0.115	%	0.0371095	1.821E-05	(kg CO2/Sm³)²
(recommended value carbon dioxide	0.23	%	)						
Water vapour	1.41	%	95 % (normal)	B	0.705	%	0.0212295	0.000224	(kg CO2/Sm³)²
(recommended value water vapour	1.41	%	)						
Emission factor model	0.799	%	100 % (rectangular)	B	0.4612314	%	0.0317103	0.0002139	(kg CO2/Sm³)²

CO2 emission factor estimate			
	Sum of variances, $u_c(C)^2$	0.0014111	(kg CO2/Sm³)²
	Combined Standard Uncertainty, $u_c(C)$	0.0376	kg CO2/Sm³
	Expanded Uncertainty (95% confidence level, k=2), k $u_c(C)$	0.0751	kg CO2/Sm³
	Value of CO2 emission factor	3.1710294	kg CO2/Sm³
	Relative Expanded Uncertainty (95% confidence level, k=2), k EC	2.3692	%

Figure 5: Uncertainty budget sheet

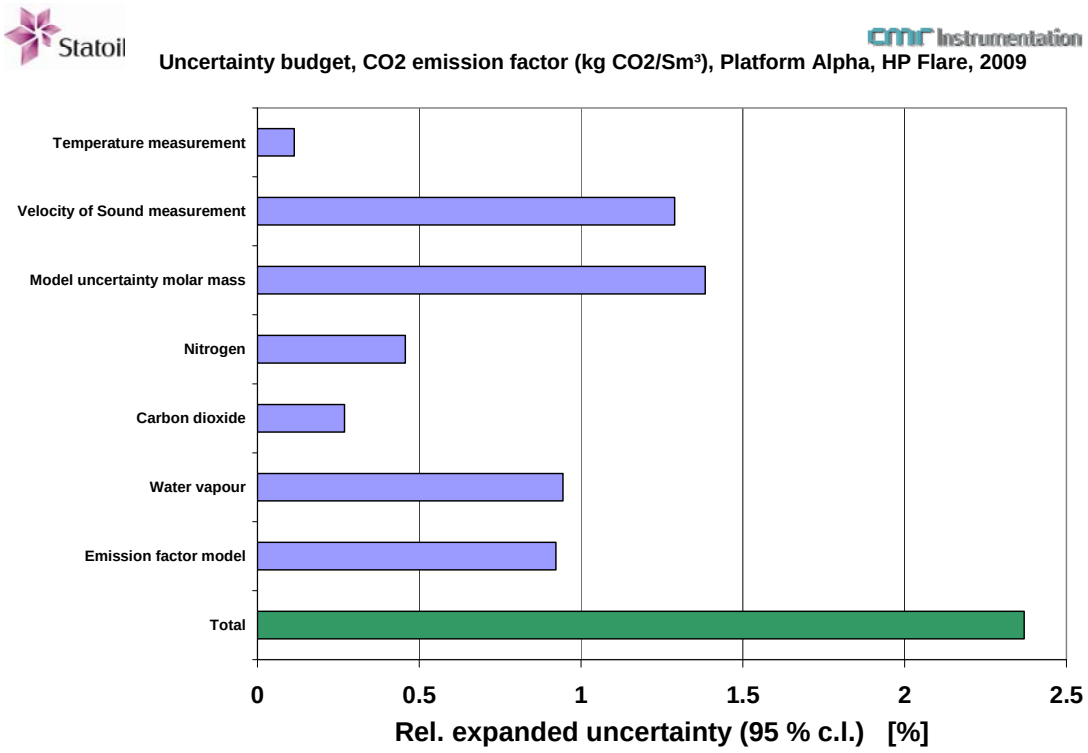

Figure 6: Plot-uncertainty contributions sheet

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CO2 emission factor in flare systems, version 1.0

CO2 - report

Name of flaring system	Platform Alpha, HP Flare	
Reporting period	2009	

	CO2 EMISSION FACTOR		CO2 EMISSION	
Time period no. 1	3.155	kg CO2/Sm³	1180	ton CO2
Time period no. 2	3.266	kg CO2/Sm³	4011	ton CO2
Time period no. 3	2.898	kg CO2/Sm³	1696	ton CO2
Time period no. 4	3.036	kg CO2/Sm³	857	ton CO2
Time period no. 5	2.995	kg CO2/Sm³	1475	ton CO2
Time period no. 6	3.140	kg CO2/Sm³	2119	ton CO2
Time period no. 7	3.209	kg CO2/Sm³	2923	ton CO2
Time period no. 8	3.141	kg CO2/Sm³	1750	ton CO2
Time period no. 9	3.031	kg CO2/Sm³	1570	ton CO2
Time period no. 10	3.066	kg CO2/Sm³	1557	ton CO2
Time period no. 11	3.255	kg CO2/Sm³	1619	ton CO2
Time period no. 12	3.459	kg CO2/Sm³	3140	ton CO2
Total	3.171	**kg CO2/Sm³**	23898	**ton CO2**
Rel. exp. uncertainty (95 % conf. level)	2.4	%		

Figure 7: CO_2 - report sheet

6 INDUSTRIAL EXPERIENCE WITH THE NEW MODEL

Per 2009 Statoil operates totally 31 offshore production facilities; and typical 1 – 3 flare gas metering systems in use on each facility.

Experience highlights:

- During first reporting period, 2009, the method have been in use for calculation of specific emission factor at 16 of 31 offshore production facilities
- By proper documentation of input data; the model have been accepted by the Norwegain Pollution Agency (KLIF / formerly SFT)
- Installations and facilities where the new method have been implemented, have experienced approximately 25% lower annual CO_2 reported quantities from flare gas systems compared to the default emission factor.
- The new method is considered as an improvement which better reflect the actual flared CO_2 quantities.
- Close cooperation between metering and process discipline is a criteria for successful implementation and use of the model
- Logging of interdependent accumulated figures (mass and standard volume) requires a logging system to be in place; some installation have required upgrade in control system
- Generation and definition of gas molar mass and inert gas content have been complex
- Model has currently no functionality for deduction of purge gas (N_2). This is possible to implement in future.
- Model not fully suitable for flare gas systems exposed with a huge span of the inert gas content; typically where produced water degassing constitutes a large fraction of the flare gas and for CO_2 removal facilities like e.g. Sleipner T.

7 CONCLUSIONS AND SUMMARY

In the present paper, a new and cost-effective method for calculation of the CO_2 emission factor for flaring systems is presented. The development of the method is motivated by the new authority requirements related to CO_2 emissions. Discussions related to these requirements have touched solutions like daily gas sampling and laboratory analyses, or online gas chromatography on the flare line. Such solutions may be technologically challenging, and are also expensive with respect to costs and man hours.

The cost-effective alternative that is presented here is based on measurements that are already performed, by ultrasonic flare gas meters. In addition, installation specific gas quality information is needed, on a general level.

An uncertainty model has also been developed for the method. An Excel program has been developed for calculation of the CO_2 emission factor, and for the uncertainty analysis. The actual uncertainty that is obtained depends on the installation, and especially on the gas composition of each of the sources of gas (like export gas, compressor gas, gas from separator, etc.) to the flare.

The new method has been taken into use on several of Statoil's installations.

8 REFERENCES

[1] Guidelines for the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council, 2006.

[2] Hallanger, A., Frøysa, K.-E. and Bjørk, R. N.: "CO_2 emission factor for flaring systems – methodology and uncertainty estimate," CMR report no. CMR-09-F10063-RA-1-Rev01, Christian Michelsen Research AS, Bergen, Norway, 2009 (Confidential).

[3] Frøysa, K.-E., Ekerhovd, H. and Johannessen, A. A.: "Nitrogen subtraction on reported CO_2 emission using ultrasonic flare gas meter," 27th North Sea Flow Measurement Workshop, Tønsberg, Norway, October 2009.