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Technical Paper

How to get confidence in reported GHG volumes

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1. INTRODUCTION

In early 2019, TotalEnergies made public its aim to reduce its net Scope 1 & 2 emissions from our operated activities by at least 40% in 2030 compared to 2015 levels and announced to reach net zero by 2050.

To live up its ambitions to which it is highly committed, TotalEnergies created in 2019 the so-called Carbon Footprint Reduction (CFR) entity. It is hosted by its Exploration & Production branch which embeds various technical and business entities spread all over the company. Five CFR roadmaps have been set up to meet the objectives by 2050. One of the various projects addresses the measurement of the Green Houses Gases (GHG) emission volume. The preliminary step of guaranteeing confidence in the volume of consumed fuel and flared gas has been entrusted in 2020 by allocation and metering specialist's entity. This project is based on the following principle: If you can't measure it, you can't fix it.

In practice volumes information comes from the integration of the flowrate over the time. To express these volumes in "standard" conditions, additional parameters are required, including physical values and gas properties, such as pressure, temperature, and density.

The level of confidence in the determination of these volumes will therefore depend on the combination of the level of each of these parameters and on the installation conditions that may not meet the manufacturers or operator's specifications.

It is therefore necessary to be able to assess this level of confidence which cannot be reduced to a 'subjective' assessment, since it would be affected by who evaluates it.

One therefore needed to rely on an 'objective' criterion, which will necessarily be numerical and then compared to a threshold of acceptance that must not be exceeded when it has been possible to be determined.

Fortunately, we found a recognized method since it is described in a specific standard. But this method requires solid mathematical skills that, as operators, we do not master sufficiently. It was also necessary that the tool used to apply this method is sufficiently reliable to be audited. We described in this paper how we worked around those constraints.

The results revealed that the level of confidence in the volumes was lower than we had initially hoped, for several reasons we present in this paper. So, we thought about how to improve these results and established enhanced or new recommendations.

2. UNCERTAINTY DETERMINATION OF GHG VOLUMES

2.1 What should an operator know about a measurement and its uncertainty?

The level of confidence of a metering system does not only depend on the meter. Indeed, the volume calculation involves pressure, temperature and density measurements at actual and standard conditions and an equation of conversion to finally convert it to standard conditions. So, we expect to have to determine the individual level of confidence of each of them.

We also know that many parameters have an influence on its level of confidence. For example, the meter and its associated pressure and temperature will behave differently considering the installation conditions and if the operating conditions are poorly located within their measurement ranges. The calibration frequency and the associated maximum permissible error to meet during their verification to a Test equipment, also play their role.

To illustrate our point here are two examples chosen from many others of influences we had to consider:

- *The geometry* associated to an orifice plate differential pressure flowmeter; It implies the reliability on the knowledge of the inner pipe and of the orifice plate diameters, on the compliance with the best installation practices about this flowmeter type and its differential pressure impulse lines.

- *The sampling method* to get the gas composition; Indeed, both actual and standard density values that are used in the flow conversion calculation depends on the representativity and frequency of it.

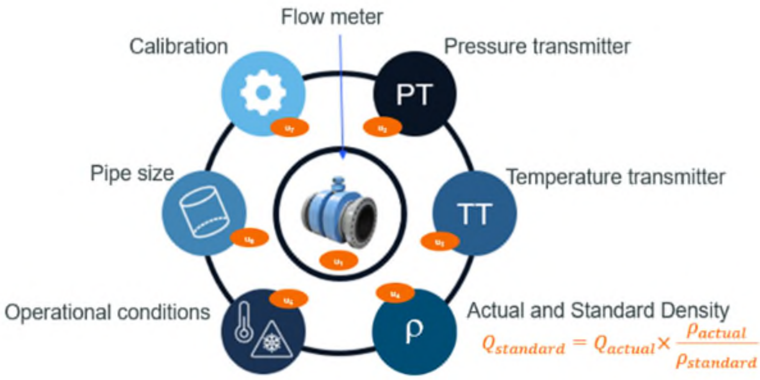
Until now we spoke about the level of confidence, but what does it stand for, and can we find a relevant indicator? Fortunately, the concept of Uncertainty covers our need. Indeed, let examine a common definition of this concept:

The Uncertainty is the quantitative expression of the level of quality of a measurement result, enabling this latter to be compared with other results, references, specifications, or standards. It is defined as the parameter associated with this measurement, characterizing the dispersion of the values that could reasonably be attributed to the variable (also called the measurand) we want to determine.

Concretely the global uncertainty of the metering system would be the combination of the individual uncertainty of each of the seven different contributors we identified, and which can be grouped in three categories:

- The primary instrument: the meter,
- The secondary instruments: Density, pressure, and temperature,
- The "industrial environment": Installation, operational conditions, and maintenance status.

Figure 1. the 7 "contributors" involved in the global uncertainty determination.



The global uncertainty will be determined as follow: $U_{Global}^2 = \sum_1^i U_i^2$ (1)

The result of the measurement is conventionally expressed as: **Y = y ± U** which is interpreted as: "the best estimate of the value attributable to the measurand Y is y, and the interval y − U to y + U is expected to encompass a large fraction of the distribution of values that could reasonably be attributed to Y ". Such an interval is also expressed as:

$$y - U \leq Y \leq y + U \quad (2)$$

The measurement uncertainty can be determined in separate ways, but the most recognized method is described in the ISO/IEC Guide 98-3:2008 "Guide to the expression of uncertainty in measurement (GUM)" and of course this one can be applied in our specific domain of gas flow measurement.

Of course, as Oil and Gas production operator we neither have the intention nor the competences to describe such method, however the objective is to share our experience of what are the minimum skills and knowledges an operator should achieve to use it correctly and provide relevant results. As you will deduce from reading this paper, for sure it has been a tough but achievable challenge for non-mathematicians we are. It has also been an exciting adventure since this method allowed us to be able to carry out and interpret these calculations with a maximum autonomy.

Consequently, what are the essentials an operator should have in mind in this domain.

The global lesson learned is, as it is suggested in the title itself of the method called "propagation of uncertainty calculations", that this "propagation", that seems a little bit mysterious for the uninitiated, betrays the fact that solving the combination we are trying to calculate, is much more subtle than applying a simple arithmetic sum of the 7 contributors.

Indeed, the complexity comes from several reasons, and we present the main ones we encountered during our study and that are, indeed, considered in the GUM standard.

First, the different "contributors" we have identified and described just before and that constitutes to the flow rate formula, do not have the same consequences on it. This mean that a slight variation of one of them could have a high impact whereas another parameter would have a low one. It is called the "sensitivity coefficient" and the consequence is that, for example, the impact on the global volume uncertainty of a parameter with a high uncertainty ("the formal term is "standard uncertainty") will be reduced if its sensitivity coefficient is small and vice versa. Consequently, those two "inputs" must be combined in the uncertainty calculations and their result help to rank the effective impact of the different parameter to prioritize the maintenance of those that have the most criticality.

This step acquired, another lesson is that arithmetically adding the absolute uncertainties leads to evaluating the most penalizing case, since we associate the extreme value of a variable with that also extreme of the next variable and so on, which become less and less likely as the number of variable increases. The square root of the quadratic sum of the uncertainty/sensitivity combination corrects this issue, leading to provide a global uncertainty more realistic, in the sense that it has the same probability to occur than that of the components.

Sometimes some of the parameters may be correlated that means they could evolve the same way and promote the penalizing case and reduce the impact of the quadratic sum. It typically happens when several parameters are calibrated by the same Test instrument.

And the less but not the least lesson learned is that the result itself is announced with a coverage factor that corresponds to the percentage of measurements involved. The most widely used is "2" that corresponds to declare that, if we examine the dispersion of the measurements, 95% of them do not exceed the calculated uncertainty. But bear in mind that this relationship between the coverage factor and the percentage is only valid if the likelihood distribution of y values follows the well-known "Normal distribution". This distribution is most often met and characterizes the fact that the spread of y values is symmetrical and concentrated around the average value. Another coverage factor we met sometimes is k=3 that expands the uncertainty but in counterpart provides more reliability (in this case 99% of the dispersion is covered). We understand easily that using a different k factor than the commonly uses distorts the interpretation and is useless. This k=2 choice is arbitrary and conventional but should be followed since it is intended to compare measurements on an equal footing.

Now if we consider the lessons learned, the first equation presented above breaks down as follows where:

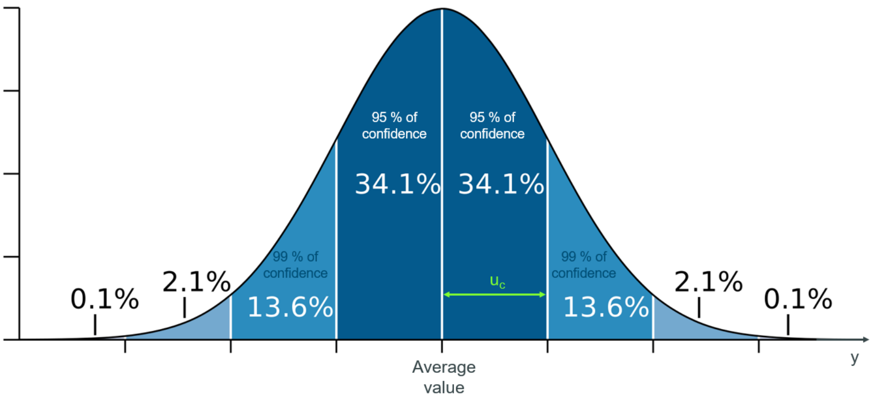
- $u(x_i)$ is the "standard uncertainty" of each "contributor",
- *Csi* its sensitivity coefficient,
- *r* the possible correlation factor with another contributor,
- $u_c(y)$ the "combined standard uncertainty" of all the contributors,
- *k* the coverage factor,
- and *U* the expanded uncertainty.

Here are respectively the combined standard uncertainty and expanded uncertainty calculation equations:

$$u_c(y) = \sqrt{\sum_{i=1}^{n} Cs_i^{\,2} \cdot u^2\,(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} Cs_i\, Cs_j\, u(x_i)\, u(x_j)\, r(x_i, x_j)} \quad (3)$$

$$U = k \cdot u_c(y) \quad (4)$$

Figure 2. Example of normal law distribution



<u>Legend:</u>

X axis: y value; Y axis: likelihood distribution of y; the distribution follows a normal law, and the dark blue area covers 95% of the total y distribution.

The expanded uncertainty will be calculated as follow for a normal distribution with 95% of confidence: $U = 2 * u_c(y)$.

2.2 Uncertainty calculation tool

Eventually thanks to the lessons we received by practicing the concept of uncertainty we were sufficiently skilled to understand the main mechanisms but also aware enough that those calculations could not be completely carried out by ourselves. The calculations through a common “Excel” spreadsheet are too complex and insufficiently robust from data quality and privacy perspective.

So, the question that arose was: "Who" or "what" can do those calculations for us? The answer was "what" to have the possibility of carrying out them ourselves, to be able to vary the multiple variables and to observe the consequences and this as often as we wish, to deepen our knowledge. This approach implies being independent of a service company which would have carried out the calculations once and for all.

The second question was: Which tool? Our list of specifications was quite substantial. These formulas should be compliant with relevant standards and not be changed easily. The calculations should be easy to carry out, applicable to all our assets and not be modified without approval. The tool itself in its globality should be approved by a recognized third party and should benefit from a support service to ensure its maintenance and answer our questions. We therefore undertook a comparative study that ends up selecting the dedicated software. The choice quickly fell on the company KELTON and its UncertaintyPlus^{TM} software because it generally met our expectations and our positive experience of using their FloCalc^{TM} software dedicated to flow calculations consolidated our choice. To test UncertaintyPlus^{TM} we compared its outcomes to both GUM WorkBench and Monte Carlo algorithm on an Orifice plate differential pressure simulation case study. We observe a very tiny difference between them that permits us to validate our choice.

2.3 Methodology

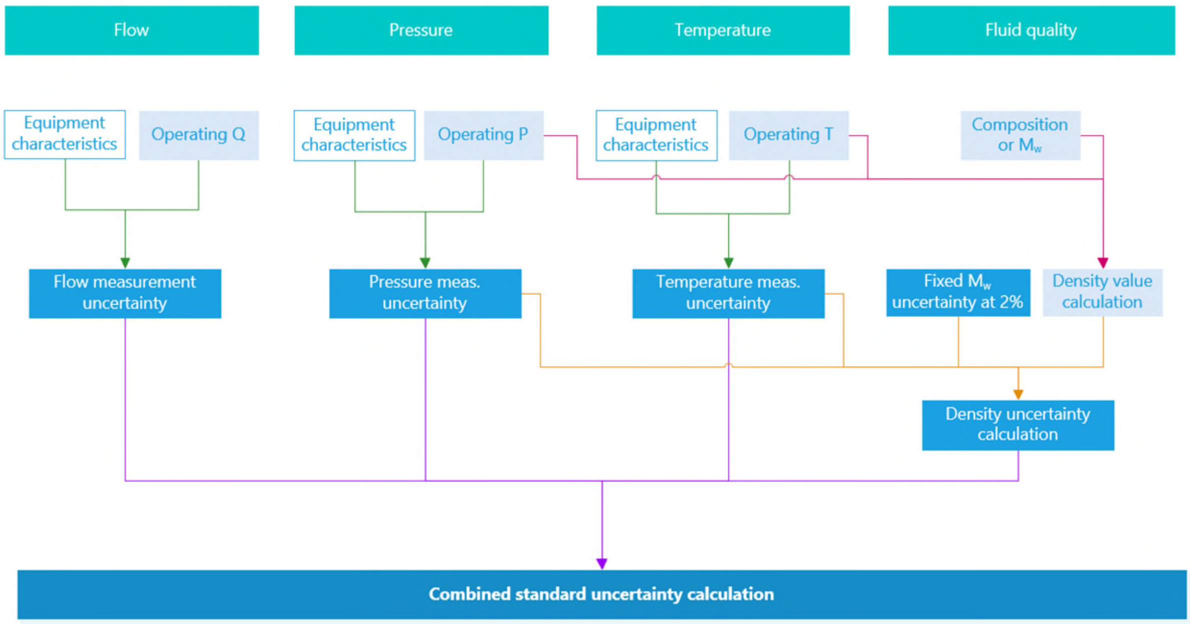
The purpose of the uncertainty calculation exercise, which has been performed in this study, is to determine for each metering system its combined standard uncertainty. This exercise required to consider the individual uncertainty contribution of all the parameters and measurements involved in the volume determination.

Each instrument involved has its own uncertainty provided by their respective vendor in the equipment datasheet. This uncertainty cannot be used alone to define a measurement uncertainty as it is affected by the operating conditions as well as their maintenance conditions. Moreover, specific operational information shall be considered as (i) the operating range of the instrument rather than the calibrated one only, (ii) the preventive maintenance, performed regularly or not (iii) the maintenance frequency and (iv) the maximum admissible error during calibration.

Here below is presented the workflow of the combined standard uncertainty calculation.

As a general introduction, notice that the 7 contributors that have been identified in the section 2.1 have been simplified into 4, since the 3 remaining ones (Calibration, Operational conditions, and Pipe size) are considered within the 4 main contributors (for instance, the flow meter calibration report outcomes will be introduced into the flow meter uncertainty calculation itself).

Figure 3. Combined standard uncertainty calculation workflow for a metering system



The equipment characteristics consists of defining all the information about:

- The instrument model, used to define its performance. Often, this is already configured in the uncertainty calculation tool,
- The instrument type, for the pressure measurement for example, it will be absolute or relative,
- The geometry of the pipeline and the instrument for the meter only,
- The ex-works uncertainty, this is the performance achievable at the factory, before to the instrument installation,
- The installation effect, considering the impact of the difference between the factory installation conditions where the instrument has been tested, and the site installation conditions,
- The measurement drift,
- The calibrated range or span,
- The calibration frequency, which has been fixed at 24 months when calibration reports are not available and,
- The maximum permissible error used during the verification.

Other parameters are required to be filled in the software for the uncertainty calculation of each instrument to have the most complete approach. Kelton software is proposing for each default values. For each, those numbers have been analyzed to assess the relevance of the proposal made by the software and modify it, if necessary.

Here is this list of additional parameters required, that have been left as defined default by the software.

Table 1. Additional inputs required for uncertainty calculation of pressure and temperature measurements

Inputs	Pressure	Temperature
Voltage difference	5 V	5 V
ΔT ambient	10°C	10°C
Detector resistance tolerance	0.01 % of reading	0.01 % of reading
ADC resolution	0.05% of span	0.05% of span
Ambient pressure uncertainty	0.02 bar	

Table 2. Additional inputs required for uncertainty calculation of flow rate

Flow rate	
Computation	0.001%
Zero stability	0.001 m/s
Velocity resolution	0.001 m/s

Table 3. Specific inputs required for uncertainty calculation of flow rate

Specifically for ultrasonic flow meter	
Meter factor	1. No proving is performed, a correction cannot be applied.
Temperature coefficient	1.093E-05 /°C
Temperature uncertainty	1.093E-06 /°C
Young's modulus	210 GPa
Young's uncertainty	6.3 GPa
Poisson's ratio	0.3

In the workflow, first, the standard uncertainty of the flow, the pressure and the temperature measurements are calculated.

The density is calculated based on the value of the following parameters:

- The gas composition or its molecular weight,
- The pressure and,
- The temperature.

The gas composition is usually not measured online but analyzed only once a year. By consequence, the following assumption has been made: the variability is low and with one analysis per year the uncertainty can be assumed at +/- 2%.

Then the combined standard uncertainty, that is also called the metering system uncertainty, is calculated by integrating the individual uncertainty of the flow, the pressure, the temperature, and the density.

Before to apply this methodology, a post treatment of input data is carried out to ensure representative calculations (outliers' measurements, data sheet extract and hypothesis taken to avoid filling unavailable inputs).

Finally, to validate the methodology, the robustness of the uncertainty calculation results has been challenged for once by performing sensitivity studies, to take a step back from the results, to ensure suitable analysis of outcomes and to provide relevant recommendations.

3. VOLUMES MEASUREMENT AND OPERATIONAL CONSTRAINT

Through this project, limitations - that were previously "intuitive" - have been quantified for all fuel gas and flare streams. For flare application, the sources of mismeasurement have been categorized as follow and have been used to evaluate the three main technologies of flare flow rate measurement installed on TotalEnergies assets:

- Sensitivity to liquid carry over and to fouling,
- Sensitivity to gas composition,
- Capability to measure at both low and high flow rates with an acceptable accuracy,
- Measurement representativity over the pipe section.

For each of the three main technologies, the associated uncertainty level has been also assessed and analyzed.

All the technical statements have been observed at site and validated with operational data.

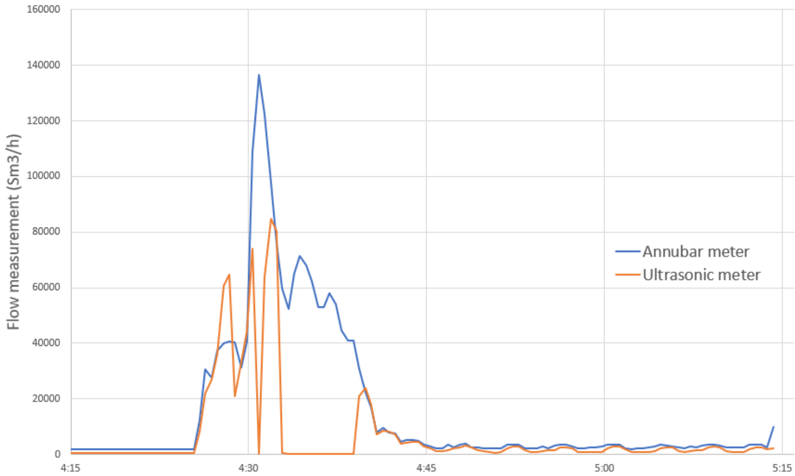
3.1 Sensitivity to liquid carry over and to fouling

Pitot tube meters signal are not affected by liquid carry over. They are measuring a pressure difference, a robust measurement that allows continuous flow reading without noticeable impact. Also, the error/overreading made on the volume flow rate is quite low and remain reasonable.

However, the thermal mass meters and the ultrasonic meters are relatively affected by liquid carry over, which generally occurs at high flow rates.

The graph below is presenting the signal of both ultrasonic and Annubar meters that are installed in series on an HP flare network. The period that has been selected is focusing on one flaring event. Before and at the event start-up, the ultrasonic and the Annubar meters are providing consistent measurements. Then the signal of the ultrasonic meter is increasing more before to drop to zero, to come back and drop again and definitively to zero until the return at low flare flow rate.

Figure 4. Loss of signal of the US flow measurement during a flaring event



The limitation of the ultrasonic flow meter is first the impact of the overspeed due to the liquid carry-over on its measurements and then the liquid saturation of transducers avoiding any measurement. At intermediate to high flow rates on high pressure flares, the liquid droplets generate systematic loss of signal. Indeed, the most likely scenario is that with droplets of liquid, the signal is first accelerating, as the speed of sound in liquid is higher than the one in the gas. Rapidly after, the signal is lost until the flare event is finished or comes back to a lower flow rate.

Consequently, in case of liquid carry-over, where the pitot tube meter will measure a little higher pressure drop and so slightly overestimating the flow rate without never losing any signal, the ultrasonic flow meter will not be able to manage biphasic fluid. This is resulting in, by using only the ultrasonic meter, an underestimation of the flared gas volume.

As it is represented on the figure, thanks to the comparison with an Annubar meter, the loss of signal is important all along the event duration.

For thermal mass, as the liquid and gas have a hugely different heat capacity, the thermal power required to maintain a constant temperature differential between the two probes will be much higher and the flow rate, proportional to this power, will be overestimated.

The operational feedback on the thermal mass meters is unanimous: the impacts of probe fouling and lack of control of the gas composition are too important.

The fouling of the probe is occurring very quickly and could lead on some installation to errors up to 100% of the measurement. Without very frequent maintenance (cleaning and calibration), the measurement cannot be kept reliable. Such interventions are not easy to perform, even more on very frequent basis.

For the Pitot, as the measurement element is intrusive, the meter is also sensitive to fouling. This will impact the pressure drop by imposing a bias on the pressure drop measurement. Regular maintenance intervention for cleaning is also required. The operational feedback is that the impact is relatively low especially with averaging Pitot tube and Annubar meter.

3.2 Sensitivity to gas composition

The ultrasonic meter is not affected a lot by the composition of the flared gas. The meter is also capable of determining the molar mass of the gas by itself.

The Pitot meter, on the other hand, needs the knowledge of gas density. This information is embedded in the K factor, usually fixed in the distributed control system, and directly used with the square of the generated pressure drop to calculate the flow rate.

Finally, the thermal mass meter is the most impacted meter since the heat capacity of the gas is required in addition to its density. This information is not properly known, even more on continuous basis.

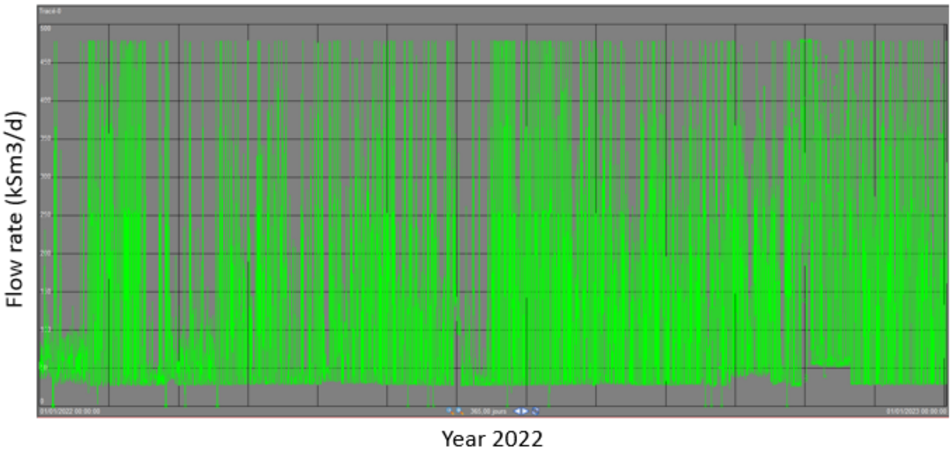
It should be noted that since the operating conditions of flares are very close to atmospheric pressure, for all technologies, the compressibility factor used to convert the actual flow rate to standard conditions is close to one and its variation is very small.

3.3 Meters rangeability

3.3.1 Capability to measure high flow rate turndown ratio

With thermal mass meter, during flaring events, on numerous installations, the maximum flow rate read by the meter is systematically exceeded, leading to this maximum value provided by the meter that is observed on the graph below.

Figure 5. Trend of a thermal mass flow meter over the year 2022



Whereas, on other installation equipped with thermal mass meter, where high flow rate is correctly measured, the routine flaring rate is below the minimum flow rate of the meter. Turndown ratio is too small for important flaring scenario.

For its part, the pitot tube meter has the possibility to extend his range using dual transmitter, thus the turndown ratio is increased from 6 to 36.

Finally, the ultrasonic meter measures flow rate with the largest turndown ratio of 200, from 0.3 m/s to 60 m/s.

3.3.2 Capability to measure the low flow rates

Pitot and some thermal mass meters can measure minimum volumes equivalent to 0.3 - 0.35 m/s. Below this threshold, some meters cannot provide stable and quite realistic measurements. However, the associated uncertainty will be important.

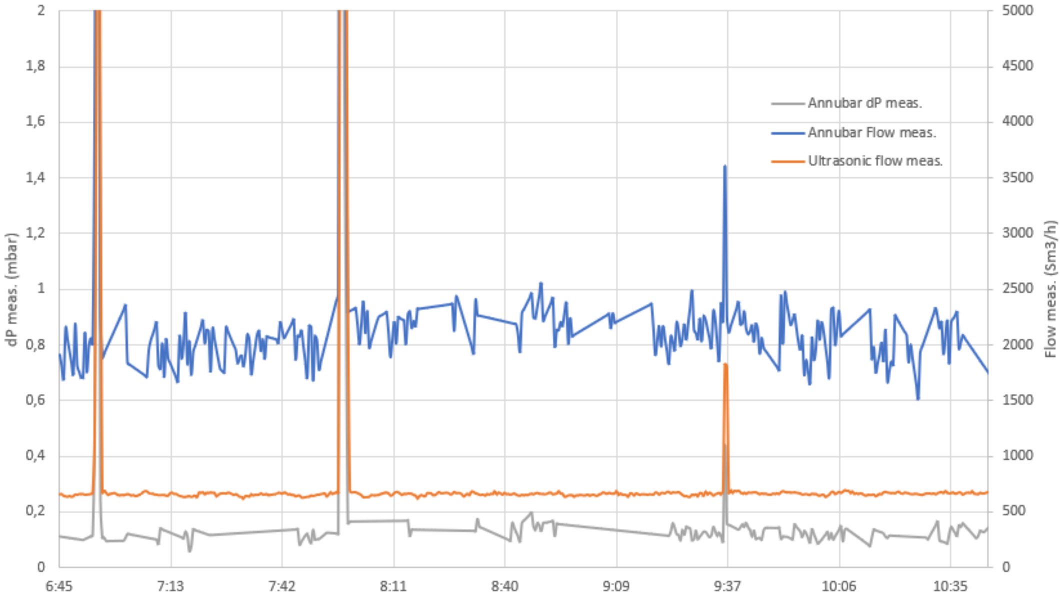
Only a very specific and recent thermal mass model can measure flow rates equivalent to 0.07 m/s, but this model is not able to measure the high flow rate case.

The ultrasonic meter can measure flow velocities down to 0.03 m/s or even 0.01 m/s. The measurement feasibility and the associated uncertainty given by the vendor are as follows:

- < 0.01 m/s → no flow measurement possible,
- Between 0.01 and 0.03 m/s → flow measurement provided with a very high associated uncertainty,
- Between 0.03 m/s and 0.3 m/s → flow measurement provided with up to +/- 20% associated uncertainty,
- Between 0.3 and 60 m/s → flow measurement provided with +/- 2 - 2.5% associated uncertainty.

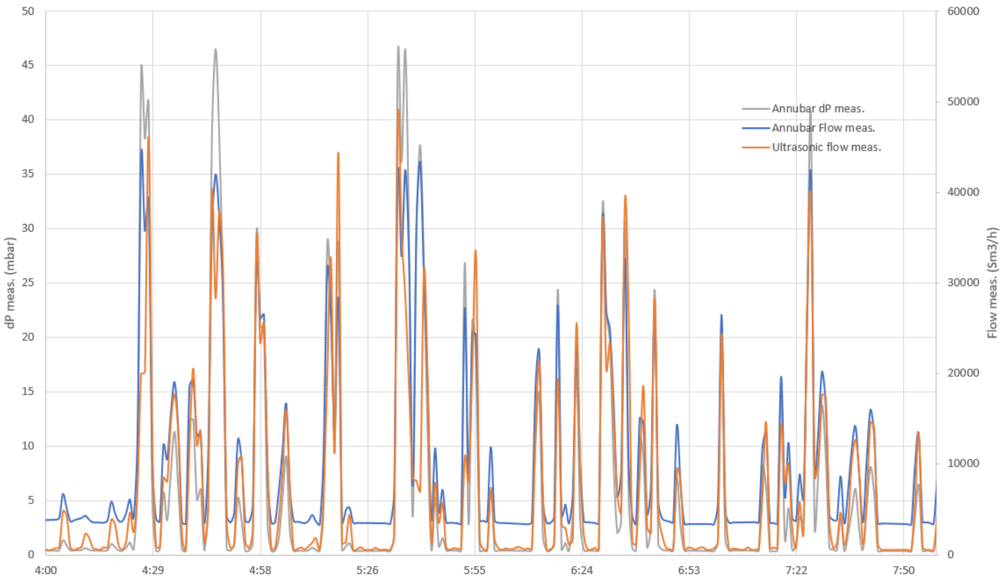
The pitot meter is not able to measure at very low pressure drop and so low flow rate corresponding usually to routine flaring. As illustrated by the figure below, in the operating range of ultrasonic measurement, the signal sent by the Pitot tube meter is providing an overestimated flow rate.

Figure 6. Annubar pressure drop and flow rate behavior at routine flaring vs. an ultrasonic meter installed in series



Same comparison has been performed and is presented on the figure below, in a medium range of flow measurement and have provided consistent signal on all the studied periods. The difference between the two flow rates, given their respective uncertainty, is considered not significant. In addition, the signal is disturbed, with the pressure drop measurement alternating between flat periods and variable periods. As the signal is too weak, the change in flow rate is not always detected by the pressure drop transmitter of the meter, as it is highlighted for the ultrasonic measurement in the above graph.

Figure 7. Annubar pressure drop and flow rate behavior at routine and safety flaring vs. an ultrasonic meter installed in series



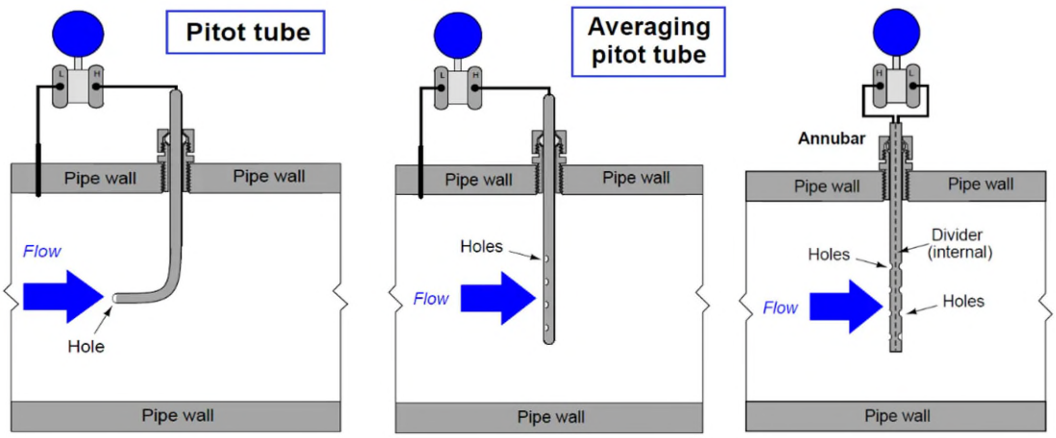
3.4 Measurement representativity over the pipe section

Thermal mass measurement is not representative of the observed flow rate over the entire pipe section: it measures the flow at one point only. If the flow profile is not homogeneous over the entire section, the flow measurement at one point will not be representative of the overall flow. Therefore, as a minimum, the thermal mass meter requires sufficient straight lines upstream to allow the flow regime to be fully developed.

Pitot tube measurement is not representative neither over the entire pipe section, for the same reason. However, averaging pitot tube and Annubar are the models installed on more recent asset to enable an average measurement along the same axis over the pipe section and thus get the most representative measurement.

Consequently, the alternative of the pitot tube is to install either an averaging pitot tube or an Annubar (see figure below). The measurement is performed at several location on one axis instead of only one point.

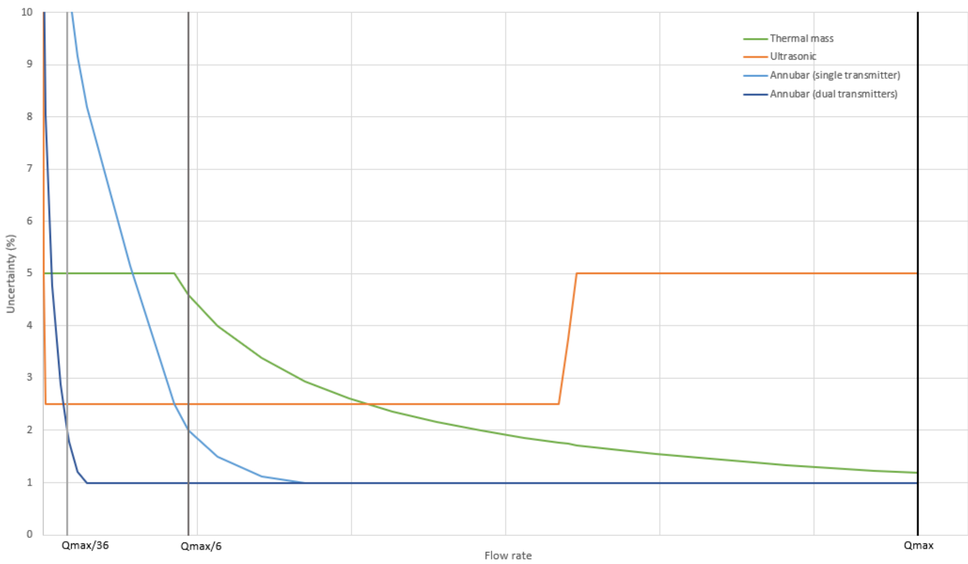
Figure 8. Pitot tube, averaging pitot tube and Annubar



Ultrasonic flow meter, historically installed on our assets were all equipped with one path only. As for averaging pitot tube and Annubar, the measurement is done on one axis of the section only. Attention is made on the upstream straight length to get a fully developed profile at the measurement section. Moreover, the ultrasonic flow meter embeds algorithms enabling to extrapolate the measured velocity on one axis to velocities measured on all the axis of the section. Today, two paths are systematically requested for new meter installation on such flare application to improve the confidence in this extrapolation.

3.5 Associated theoretical uncertainty level

Figure 9. Comparison of the primary uncertainty estimation for the three main meter technology for flaring (at optimum operational conditions)



Uncertainties' values have been extracted from the vendors' datasheet.

Note: It is assumed here that the meter, whatever its technology, is equipped with dedicated temperature and pressure measurement. Thus, the impact on the uncertainty of the standard volume will be equivalent whatever the technology is. Therefore, the above graph has been expressed as a function of the flow rate only at actual conditions.

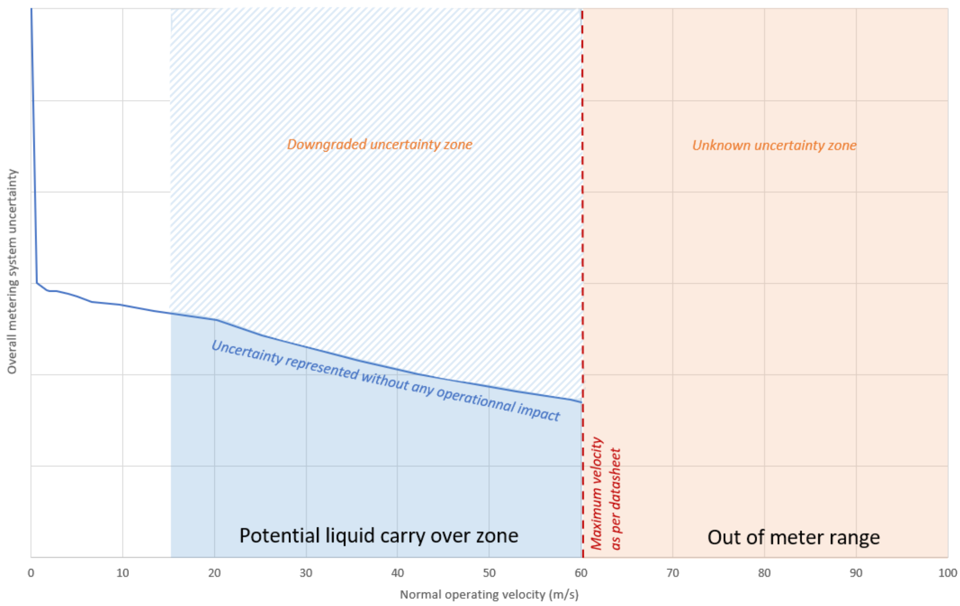
At very low flow, the uncertainties of all meter technologies are very high.

In the routine flaring scenario and at very low flow rates, the uncertainty of the primary instrument also named primary uncertainty (under optimal flow loop operational' conditions) of the thermal mass is 5%. This uncertainty is expressed at actual conditions, whereas the target is 5% at standard conditions. Knowing that conversion to standard conditions involves adding the uncertainties of pressure and temperature measurements as well as composition (even if composition impact is limited considering the operating pressure of the flare system), this target at standard conditions cannot be achieved. This overall uncertainty at standard conditions is then around minimum 10% with optimal operational and maintenance conditions.

Consequently, the thermal mass is assigned by a primary uncertainty of between 2 and 5% in the literature, but up to 10 to 30% minimum in practice.

Then, the graphic below is representing the flow uncertainty behavior of a metering system equipped by an ultrasonic flow meter as a function of flow rate.

Figure 10. Uncertainty behavior of a metering equipped by an ultrasonic flow meter, over its whole flow rate range.



With liquid carry over, at a velocity within the operating range of the meter, the uncertainty is downgraded and could be at any higher value.

3.6 Substitute solution

Measuring a flare volume is nowadays one of the main metering challenges. The technology shall not be sensitive to gas composition and to fouling. It shall be made at several points of the section to be the most representative whereas flare pipeline could have high diameter. The technology shall offer a very large turndown ratio as flare measurement is varying between very low flow during certain cases of safety (gas sweeping for example) and during routine flaring, and very high flow rate during depressurization event. Moreover, the target is clear in terms of flare measurement quality, it shall be reliable and provides satisfying associated uncertainty.

In the recent years, ultrasonic meter and then Averaging pitot tube or Annubar meter have clearly became the recommended solutions, either alone for ultrasonic or in series.

For other existing assets, as only one flare meter cannot answer all these requirements, as the instruments are not 100% of time reliable, to compensate their limitation, virtual flow measurements have been developed to compensate the limitation of flowmeter in place and therefore to get access to flare volume all the time.

In parallel, works are still ongoing as TotalEnergies is willing to decipher how the meter is behaving over the operating range and better understand where the limitations are. The objective behind is to find appropriate installation arrangement to avoid, whenever possible, any signal perturbation and to define the suitable limit of meter. For those reasons, teams are also working to connect ultrasonic flow transmitters with Modbus to the supervision system, which was not the standard, enabling to retrieving additional information than the flow rate as speed of sound, signal-to-noise ratio, etc. This online and permanent connection will allow to catch information during the flaring event.

The control of the measurement limits is essential for the definition of the substitution solution use. This has made possible also to anticipate some requirement in terms of installation for this substitute solution.

4. VFM

4.1 Context

Ultrasonic technology has been selected as the most accurate technology on low flow rate and on all its full range provided that there is no overspeed and/or liquid carry in the flare line. As a matter of fact, when the velocity is very high, liquid droplets are carried over. This liquid disturbs the signal as each droplet of liquid seen by the meter involves a loss of signal. Finally, these perturbations lead to an underestimation of the reported flare volume

Virtual flow metering models have been built to be used as a substitute solution in such cases for flaring gas volume determination. This solution is answering specific operating cases, namely high-pressure flare equipped with an ultrasonic flow meter and facing liquid carry-over, as such virtual flow metering model is requiring, for its construction, accurate pressure, and flow rate measurements.

Consequently, this methodology of flare volume determination is only applicable to high pressure flare network. Low pressure measurement is too close on its full range of operation, to the minimum instrument measurement. Combined to a non-adapted measurement range, typically a 0-10 bar designed for process requirement, the associated accuracy of such measurement is not sufficient for the model establishment.

For the flow rate, building VFM is only possible with the ultrasonic flow meter considering a range of operation above 0.3 m/s and below 30-60 m/s, the threshold of overspeed and/or liquid carry over. Outside this range and with the other technologies, the measurement is not sufficiently accurate.

Any error in the measurements involves the absence of linearity in the correlation that is presented later in this document.

4.2 What VFM stands for

The section of pipe between the flare meter and the flare itself is considered as behaving like a big differential pressure device.

This substitute solution, also called VFM (Virtual Flow Meter), is a correlation-based method using:

- KO Drum operating pressure and temperature measurements,
- and the pressure drop between the KO drum and the flare tip which is at the atmospheric pressure.

The flow rates are then given with the following correlation or VFM: $Q_{Flare} = K\sqrt{\Delta P \times \frac{P}{T}}$.

With K the K factor
ΔP the differential pressure between the pressure of the flare K.O. drum and the atmospheric pressure
P the pressure at the flare K.O. drum (in Pa absolute)
T the temperature (in °K)

The correlation is established with the flare volumes measured when there is no liquid entrainment, below a certain threshold of flow rate/velocity in the pipeline.

The K factor can be estimated using the ultrasonic flare meter reading at its most reliable working range.

The VFM K factor is also determined for a minimum pressure of about 0.4 barg which is equivalent to a $\sqrt{DP \times \frac{P}{T}}$ of 0.04. Below, the uncertainty of the pressure measurement is considered too high to be acceptable and allow to be confident in the K factor determination.

Typically for a pressure measurement range of 0 – 10 barg, an uncertainty of pressure measurement 1% represents 10 mbar.

The 20 mbar represents 5% of the measurement at 0.4 barg. This 5% has been considered as the minimum required to get reliable results.

Above this pressure limit of 0.4 barg, the pressure and the velocity are in the optimal operating range for a flow meter and a pressure measurement.

On some flare systems, the liquid carry over is observed from a $\sqrt{\mathrm{DP} \times \frac{\mathrm{P}}{\mathrm{T}}}$ at 0.05 (about 0.5 barg of pressure in the KO drum).

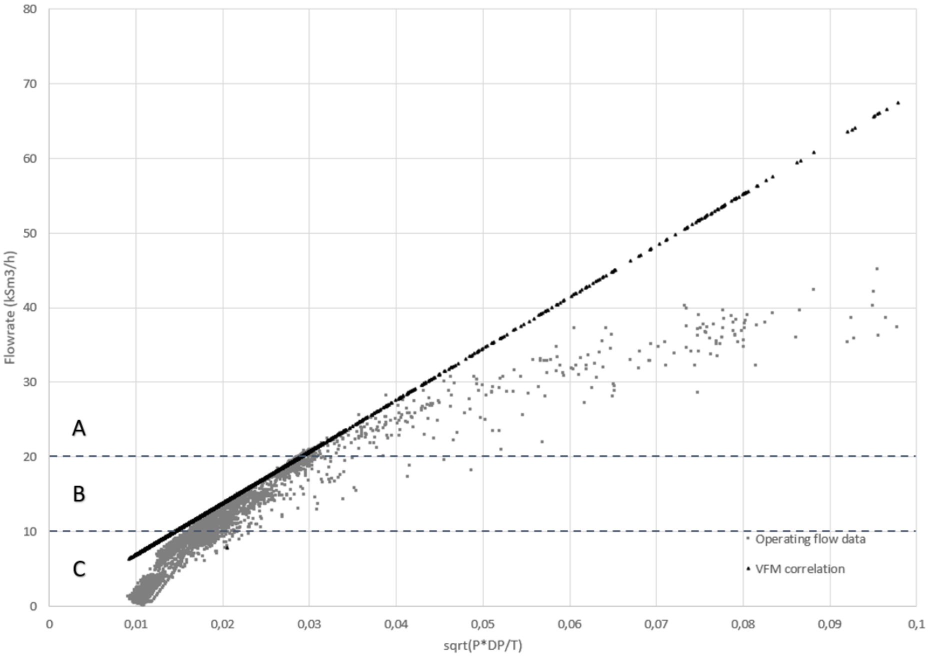
4.3 VFM application

Measurements of the available instruments (i.e., temperature, pressure, and pressure difference with atmospheric pressure) have been extracted over a defined period and have been combined under the square root.

The associated flow rate measurements have been then represented on a graph in function of the square root result for visual analysis and validation of the methodology application. The proportionality between the flow rate and this square root (dP*P/T) is expected and represented by a straight line corresponding to the K factor. This factor considers the constant (above a certain Reynolds, i.e., a certain velocity), made up of all the other parameters to which we do not have access (mainly the discharge coefficient and the virtual orifice restriction).

4.3.1 Case number 1

Figure 11. VFM application to operational flow data.



The correlation has been established by selecting a K factor to match the middle-range data.

The area in which this straight line can be established, requires sufficient accuracy on both meter and pressure sensor sides, i.e., a minimum flow rate/speed/Re (see above). This is particularly true at low values as the operating pressure is very close to atmospheric one and consequently in the very low range of the pressure sensors. For this reason, we consider the values only above 0.015 for sqrt(dP*P/T).

Low values are too impacted by poor accuracy on the pressure measurement.

High values are impacted by flow measurement's loss of signal.

In area A, above a certain limit of velocity or flowrate, the systematic use of the VFM is recommended as a backup of the ultrasonic flow meter due to observed.

In the area B, the VFM should be used if the difference between the meter and the VFM is above their expanded uncertainty measurement.

In the area C, the ultrasonic flow measurement shall be used as operating in its accurate range without any perturbation.

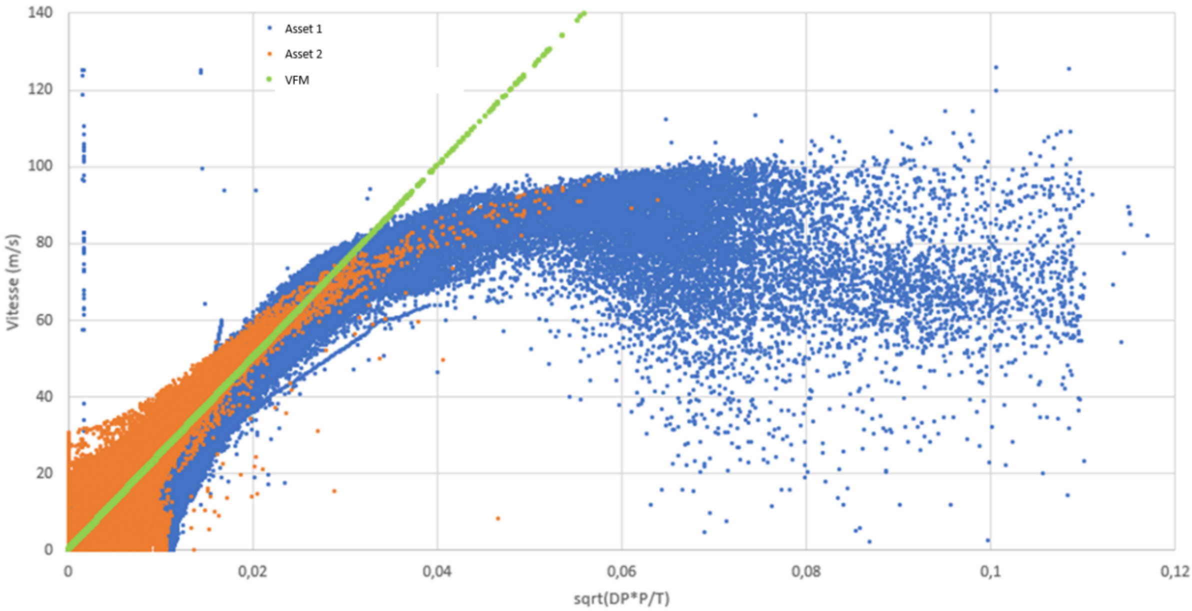
4.3.2 Case number 2

Here is the VFM representation for two of the TotalEnergies assets equipped by an Ultrasonic meter that is named "model 1".

Both meters have similar behavior on the common flow range, from zero to "medium" flow rate, in the range of normal operating flow rate of the ultrasonic meter. From 60 m/s onwards, the curves no longer follow the proportional straight line between velocity and square root. As the square root increases, the meters begin to underestimate the flow rates (the curves bend). Then above a certain square root a wide disparity in flow rates is observed, followed by saturation (around 100 m/s in the case of asset 1).

For such applications, the VFM would have to be applied from a velocity of 60 m/s.

Figure 12. VFM application to Ultrasonic model 1.



4.3.3 Case number 3

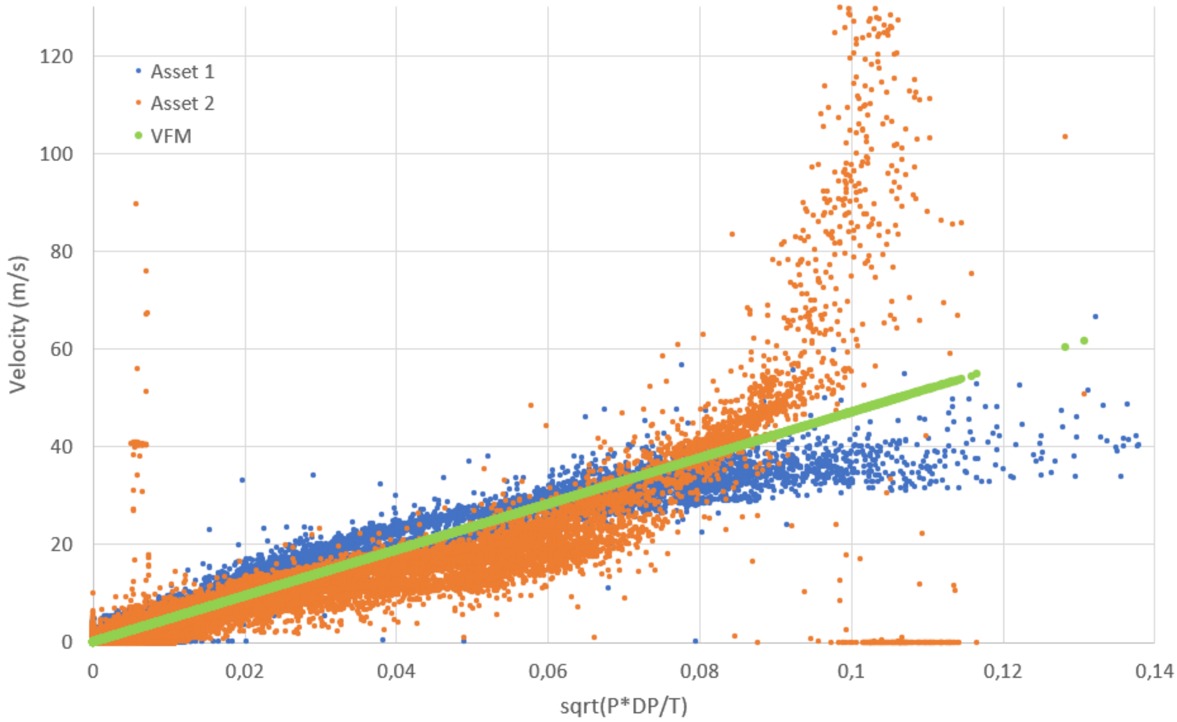
Here is the VFM representation for two of TotalEnergies assets equipped by an ultrasonic meter named "model 2".

As per the datasheet, both meters of each two assets should be able to measure the velocity from 0.03 to 120 m/s. However, the two curves have a different behavior.

The curve of the asset 1 observes a change in the slope from the threshold of 30 m/s. Above this limit, the velocity is lower than the expected one, which could be the indication of loss of signal (potentially coming from the presence of liquid droplet, and liquid carry over). On the contrary, the asset 2 increases suddenly, also from this threshold of 30 m/s, which could indicate an over counting due to overspeed phenomenon.

For such applications, the VFM would have to be applied from a velocity of 30 m/s.

Figure 13. VFM application to Ultrasonic model 2.



4.3.4 Other cases

If the pressure and/or the flow rate are not reliable enough, the VFM definition is not possible. In such case, the VFM representation does not make sense as illustrated on the example below. For one flow rate measurement, many different pressures are measured, which is mathematically impossible.

Figure 14. Unfeasible VFM model - Asset A

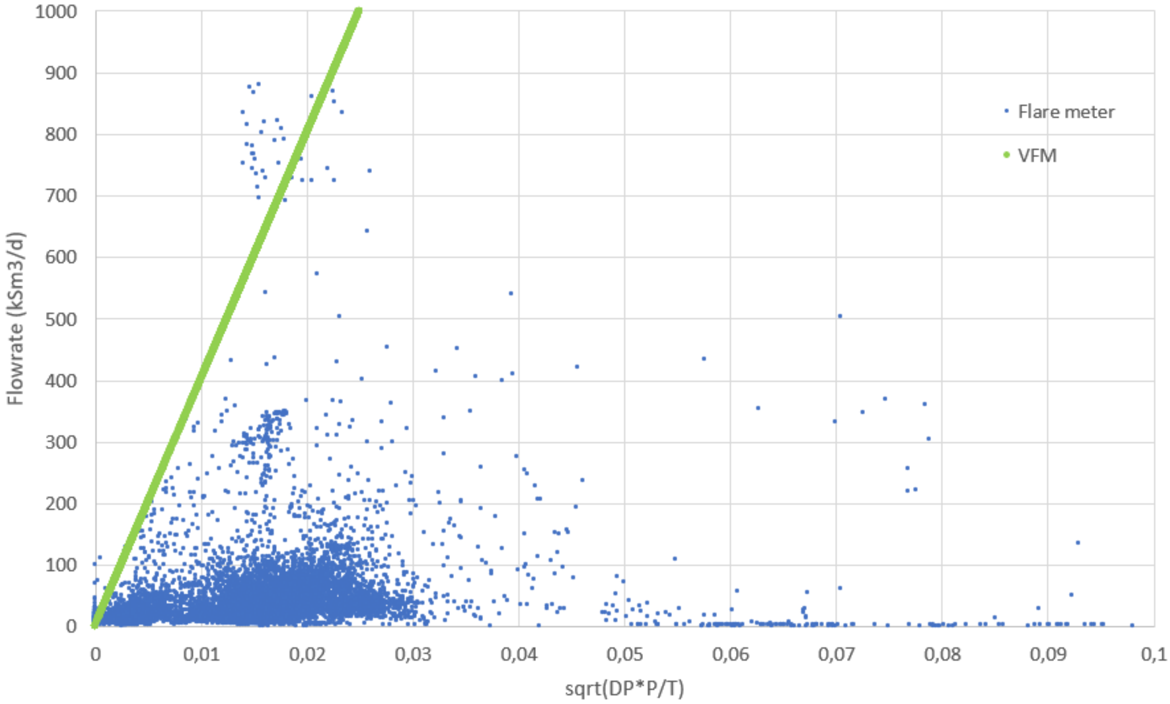


Figure 15. Unfeasible VFM model - Asset B

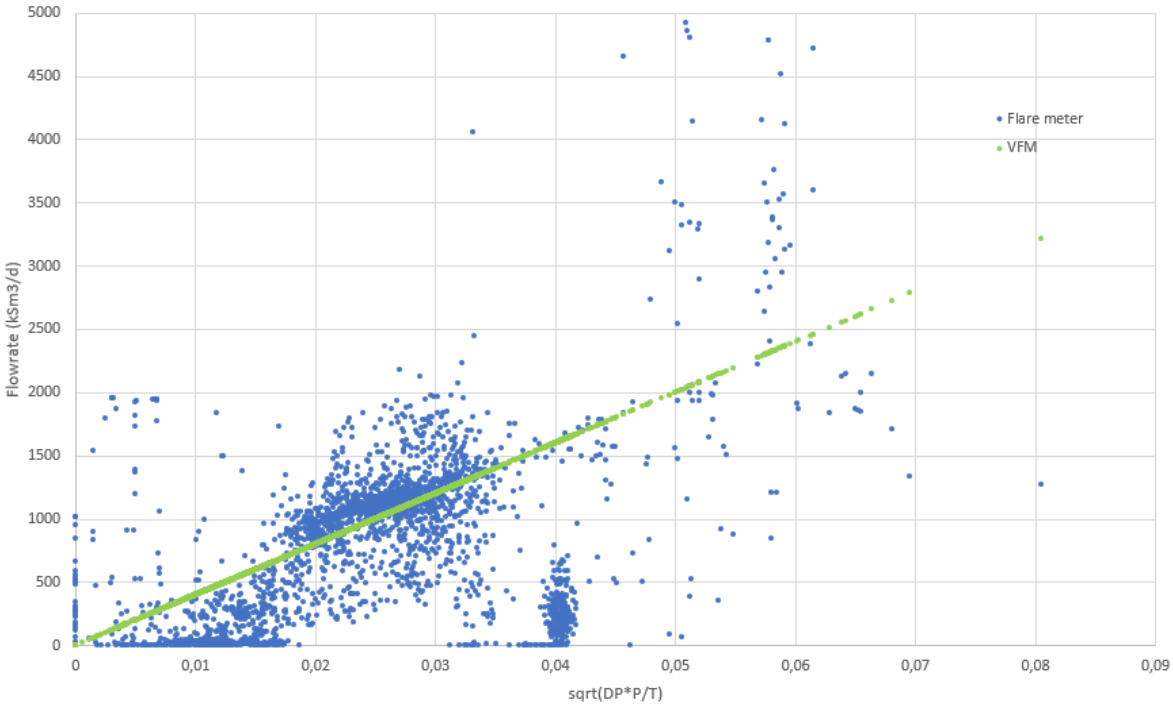
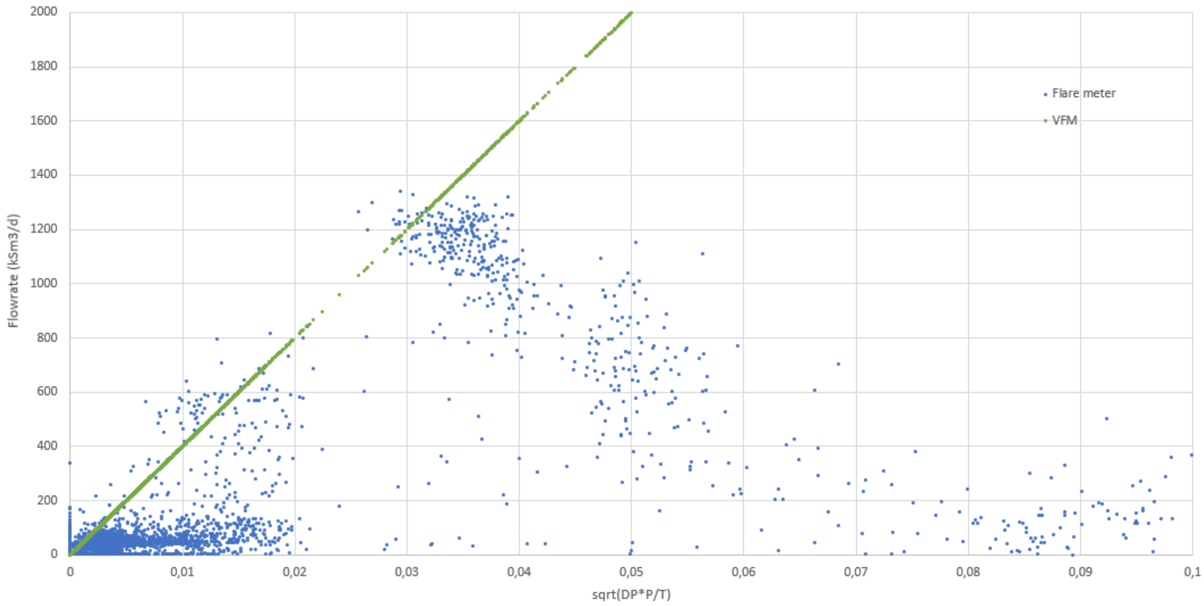


Figure 16. Unfeasible VFM model - Asset C



Those use cases reinforce the necessity of having accurate pressure measurement at pressure close to atmospheric pressure. In addition, VFM cannot be determined if the measurement at low and medium flow rate is not feasible and accurate.

4.4 Uncertainty calculation

The benefit of the VFM solution immediately brings additional questions about the confidence that can be attributed to this method, the appropriate used in terms of operating conditions. This has been covered using a specific uncertainty calculation workflow - as not available from shelves.

4.4.1 Method description

A specific uncertainty calculation method has been developed based on statistics calculation whose workflow has been programmed in an excel sheet as follow:

1. Specify the measurand Y
2. Write the mathematical relationship between the measurand Y and the input quantities X_i : $Y = f(X_1, X_2, \ldots., X_n)$

For our VFM application, the formula is the following $Q_{Flare} = K\sqrt{\Delta P \times \frac{P}{T}}$. This formula is used in two separate ways:

- o Case 1 - The Q flare is given either by the ultrasonic meter to evaluate the K factor with $K = \frac{Q_{Flare(US)}}{\sqrt{\Delta P \times \frac{P}{T}}}$

- Case 2 - Or the Q flare is the predicted flare flow rate using the K factor determined above with $Q_{Flarepredicted} = K\sqrt{\Delta P \times \frac{P}{T}}$

The ΔP is the pressure differential between the KO drum and the atmosphere, also expressed by P_{KODrum}-P_{atm}.
The P is the KO drum pressure, and the T is the KO drum temperature.

3. Identify all sources of uncertainties:
   - Case 1: Q flare provided by the ultrasonic meter, $P_{KO\ drum}$, P_{atm}, and $T_{KO\ drum}$
   - Case 2: K factor, $P_{KO\ drum}$, P_{atm}, and $T_{KO\ drum}$.
4. Identify if there are any dependent correlated input quantities: this is not the case for our VFM application.
5. Determine the period on which the VFM will be established, to select the operating data for the flow rate provided by the US meter, the KO drum pressure, and the temperature measurements.

The number of data selected is between 20 and 30 around a value of 0.04 for $\sqrt{\Delta P \times \frac{P}{T}}$ which is the minimum threshold for the VFM application.

6. For each parameter X_i (US flow rate, KO drum pressure and temperature), calculate the average value over the selected set of data. These values will be used as operating value for the uncertainty calculation.
7. For each parameter, the dispersion is determined on the selected set of data by the calculation of the standard deviation.
8. For each parameter, based on its standard deviation, the associated standard uncertainty is determined as being equal to $\sigma/\sqrt{n}$..
9. Calculation with UncertaintyPlus™ of the standard uncertainty for each parameter (US flow rate, pressure, and temperature) based on installed equipments' datasheet.
10. The atmospheric value is looked for each timestamp of the selected data set. An average value is calculated to be used in the uncertainty calculation.
11. Calculation with UncertaintyPlus™ of the atmospheric pressure standard uncertainty.
12. Calculate the standard uncertainty $u(\bar{X_i})$ for each X_i either as Type A evaluation or as Type B evaluation.

Type A corresponds to the uncertainty link to the data dispersion. Whereas the type B corresponds to the uncertainty linked to the equipment performance itself. This second calculation is made using the datasheet information.

13. Calculation of the combined uncertainty for each parameter, by adding the standard uncertainty provided by UncertaintyPlus™ and the standard uncertainty linked to the measurements' dispersion.
14. Calculation of sensitivity coefficients of the K factor in relation to each parameter of the VFM formula (US flow rate, KO drum pressure, KO drum temperature and atmospheric pressure) by applying a derivative formula as follow: $C_i = \frac{\partial y}{\partial x_i}$
15. Calculate the combined Uncertainty U of the K factor and then the expanded uncertainty using a coverage factor k of 2 (for a level of confidence of 95%).

$$u_c(y) = \sqrt{\sum_{i=1}^{n} Cs_i^{\ 2} \cdot u^2(x_i)} \qquad \text{and} \qquad U = k \cdot u_c(y)$$

16. Repeat step 14 for the parameter "predicted flare flow rate" (application case 2) in relation with (K factor, KO drum pressure, KO drum temperature and atmospheric pressure).
17. Calculation of the predicted flow rate standard uncertainty and then its expanded uncertainty using the same formula than step 15 and with the same level of confidence.

This methodology has been applied to one asset and has provided the following results:

Table 4. VFM uncertainty – Step 1 - K factor uncertainty calculation result

Parameter	Operating value		Expanded Uncertainty (U_i)	Standard Uncertainty (u_i)	Sensitivity coefficient (c_i)	u_i x c_i
Q	7,25	Sm3/s	5,809E-01	2,904E-01	2,355E-04	4,676E-09
T	313	K	3,400E+00	1,700E+00	2,722E-06	2,140E-11
P_{atm}	101157	Pa	8,979E+02	4,490E+02	2,131E-08	9,150E-11
$P_{KO\ drum}$	141198	Pa	5,219E+03	2,609E+03	-2,735E-08	5,092E-09
K factor	0,001706174	unitless				

		Absolute	Relative (%)
K factor	Combined relative uncertainty	9,941E-05	**5,826**
	Expanded uncertainty (95% confidence)	1,988108E-04	**11,652**

Table 5. VFM uncertainty – Step 2 – Flow rate uncertainty calculation result

Parameter	Operating value		Expanded Uncertainty (U_i)	Standard Uncertainty (u_i)	Sensitivity coefficient (c_i)	u_i^2 x c_i^2
K factor	0,0017	-	1,988E-04	9,941E-05	4,2472E+03	1,782E-01
T	313,4269	K	3,400E+00	1,700E+00	-1,156E-02	3,861E-04
P_{atm}	101156,5517	Pa	8,979E+02	4,490E+02	-9,049E-05	1,650E-03
$P_{KO\ drum}$	141197,8568	Pa	5,219E+03	2,609E+03	1,161E-04	9,186E-02
Q	7,25	Sm3/s				

		Absolute	Relative (%)
Flow (Q)	Combined relative uncertainty	5,21671E-01	**7,199**
	Expanded uncertainty (95% confidence)	1,043E+00	**14,398**

The VFM uncertainty has been estimated at roughly 14%, which is higher than the one of the equipment itself. However, we know by having studied the physics than the VFM value is close to the true value despite the higher uncertainty.

4.4.2 Validation tools of the method

To validate the combined method of UncertaintyPlus™ and excel calculation, two validations have been performed successfully with:

- First the GUM WorkBench software which has not been selected as the main method due to limited number of digits in the result, limiting the result accuracy.
- Then the Monte Carlo algorithms programmed in an excel sheet by the TotalEnergies metering engineers.

Here below the results of flow rate uncertainty calculated with the three methods.

Table 6. Method comparison of VFM uncertainty calculation

Method	Uncertainty results (%)
VFM	14,398
GUM WorkBench	14,408
Monte Carlo	14,431

The discrepancy with Gum workbench is due to the limited number of digits provided by the tool.

Whereas the difference observed with Monte Carlo is not significative as it is explained by the automatic random generation of values.

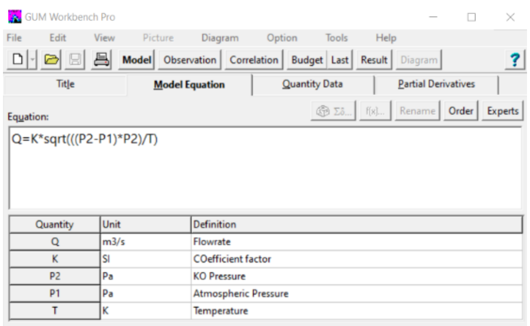
Consequently, the three methods are converging, that is validating the uncertainty calculation of the VFM.

4.4.2.1 With GUM WorkBench

This software applies the step 14 to 17 of the principal method.

The VFM correlation is defined in the software along with the key parameters as shown below:

Figure 17. VFM equation in GUM WorkBench



The operating values and their associated standard uncertainty are manually configured in the software as inputs of the following calculations.

The list of inputs required is presented in the figure below. The inputs required are the same for each parameter.

Figure 18. Example of input values required for uncertainty calculation each parameter

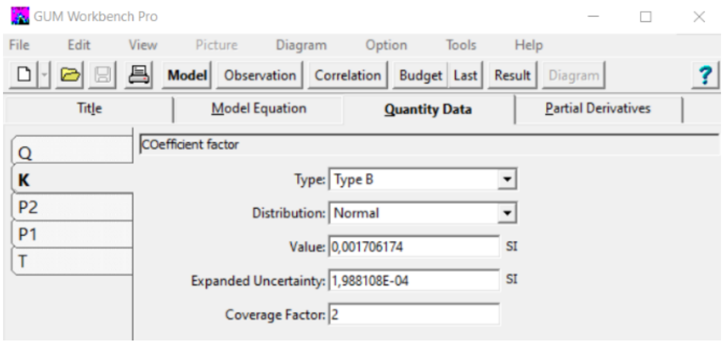


Table 7. Required inputs for GUM Workbench method

Inputs	Comments
Type	Type A or B
Distribution	According to the normal, rectangular, or derived distribution law
Value	
Expended uncertainty	
Coverage factor	Depends on the expected level of confidence

Then, the sensitivity coefficients for the K factor are determined to calculate its associated uncertainty.

Finally, the same exercise is performed on the flow rate parameter to determine the expanded uncertainty of the flow rate provided by the VFM.

The sensitivity coefficients are determined by using partial derivatives of K factor first and then of the flow as presented in the figure below.

Figure 19. Partial derivatives calculation for sensitivity coefficients of flow ate determination

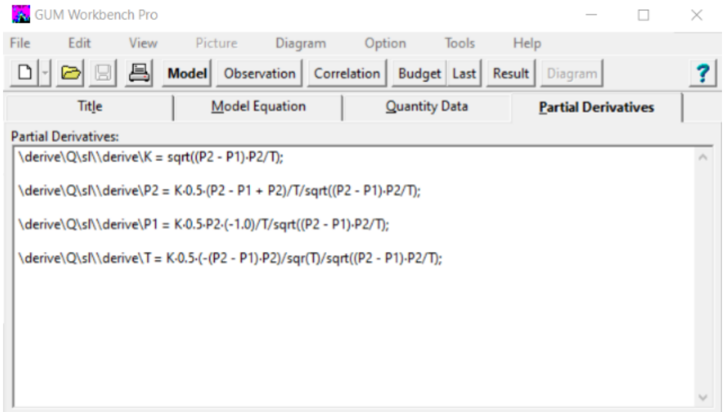
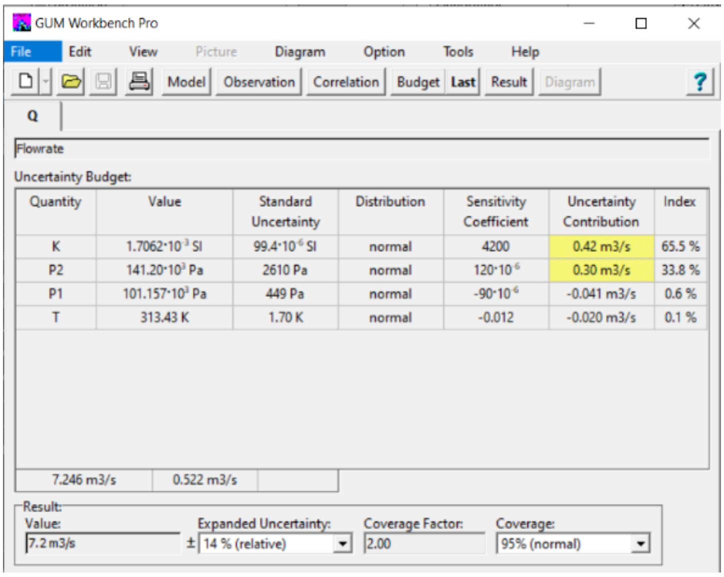


Figure 20. Results provided GUM Workbench



The expanded uncertainty is equal to the ratio of uncertainty value divided by the quantity given with 3 digits.

4.4.2.1 With Monte Carlo algorithms

This information required to complete the calculation with Monte Carlo are the same that the ones for the GUM Workbench. As for GUM WorkBench, the steps 14 to 17 of the principal method are applied.

The principle of the Monte Carlo method is to estimate quantities using simulation of random variables. The simulations predict the probability of different outcomes when the intervention of random variables is present. The random variables or inputs are modeled based on probability distributions such as normal, log normal, etc. A minimum of 1000 simulations is fixed by the method to achieve satisfying results in terms of probability.

The table below shows an example of results by applying this method. The interesting point is the uncertainty difference with the iteration number and the associated resulting error. This error is at 0 after 100 000 of iteration, whereas the discrepancy on the uncertainty evaluation is less than 0.05% for an uncertainty at 14.431%. The minimum of iteration required at 1000 has been by consequence, considered as too limited and the results used for the verification are taken for 100 000 of iteration.

Table 8. Example of Monte Carlo method results – K factor uncertainty

N°Iterations	Ecartype	Moyenne	U% K	%ErreurRelatif
100	0,00020	0,00172	11,769%	1,0574%
1000	0,00020	0,00171	11,712%	1,5369%
2000	0,00020	0,00172	11,888%	0,0524%
5000	0,00021	0,00172	11,978%	0,6993%
10000	0,00020	0,00172	11,881%	0,1183%
15000	0,00020	0,00172	11,879%	0,1330%
20000	0,00020	0,00172	11,854%	0,3403%
25000	0,00020	0,00172	11,890%	0,0412%
30000	0,00020	0,00172	11,869%	0,2166%
35000	0,00020	0,00172	11,867%	0,2292%
40000	0,00020	0,00172	11,867%	0,2291%
45000	0,00020	0,00172	11,891%	0,0351%
50000	0,00020	0,00172	11,900%	0,0443%
55000	0,00020	0,00172	11,891%	0,0277%
60000	0,00020	0,00172	11,893%	0,0120%
65000	0,00020	0,00172	11,883%	0,0970%
70000	0,00021	0,00172	11,905%	0,0825%
75000	0,00021	0,00172	11,913%	0,1513%
80000	0,00020	0,00172	11,893%	0,0183%
85000	0,00020	0,00172	11,894%	0,0075%
90000	0,00020	0,00172	11,890%	0,0394%
95000	0,00020	0,00172	11,891%	0,0328%
100000	0,00020	0,00172	11,895%	0,0000%

Table 9. Example of Monte Carlo method results – Flow rate uncertainty

Number of iterations	Standard deviation	Mean	Uncertainty	Relative error
100	1,005152804	7,300218	13,769%	4,5907%
1000	1,018426726	7,26126015	14,025%	2,8121%
2000	1,05932075	7,2370582	14,637%	1,4285%
5000	1,046920553	7,23107652	14,478%	0,3241%
10000	1,046416678	7,22591299	14,481%	0,3475%
15000	1,045213946	7,23130739	14,454%	0,1573%
20000	1,046252888	7,23349113	14,464%	0,2266%
25000	1,046461305	7,22893369	14,476%	0,3098%
30000	1,042295998	7,23123882	14,414%	0,1213%
35000	1,044267321	7,2320203	14,439%	0,0568%
40000	1,043313985	7,23363168	14,423%	0,0568%
45000	1,043923676	7,23625627	14,426%	0,0347%
50000	1,042984963	7,23373336	14,418%	0,0898%
55000	1,042619799	7,2352211	14,410%	0,1453%
60000	1,042496229	7,23425497	14,411%	0,1438%
65000	1,043276901	7,23534534	14,419%	0,0841%
70000	1,043147211	7,23462448	14,419%	0,0865%
75000	1,04315517	7,23505079	14,418%	0,0917%
80000	1,044500467	7,23519579	14,436%	0,0352%
85000	1,04382444	7,23463746	14,428%	0,0218%
90000	1,044873107	7,23546399	14,441%	0,0672%
95000	1,044844182	7,23670168	14,438%	0,0473%
100000	1,044239046	7,23592984	14,431%	0,0000%

5. CONCLUSION

After 2 years and an half, the project' set-up and deployment, enabled to generate significant numbers of deliverables on many aspects. This internal approach was performed free of any service company, which would have carried out the calculations once, but without any means of continuous improvement.

Reviewing the full GHG emission volume process in depth, was the opportunity to correct calculation errors within flow calculator and real-time data management system.

The flare meter behaviors are not homogeneous. The meter accuracy highly depends on gas speed, flow profile and technology itself. Limitations have been assessed and quantified for all fuel gas and flare streams.

For flare application, the sources of mismeasurement have been categorized and used to evaluate the three main technologies installed on TotalEnergies assets. Substantial progress has been made in understanding these mismeasurements, allowing us to put in place recommendations from a design and operational point of view, and to go further in overall comprehension. This being said, there is still room for improvement by either upgrading the instruments communication or the equipment's themselves or by defining alternative solutions.

Virtual flow metering models have been built to be used as a substitute solution in case of high-pressure flare equipped with an ultrasonic flow meter and facing liquid carry-over. VFM use cases reinforce the necessity of having accurate pressure measurement at pressure close to atmospheric pressure. The uncertainty associated with this approach is higher than the one of the metering points itself; however, the VFM outcome is certainly closer to the true value. In any case, pressure and flow rate measurement remain critical to ensure reliable GHG volume estimations and associated as-low-as-possible uncertainty, based on metering point or on substitute solution.

Another key achievement was the set up of a robust combined standard uncertainty template for both flare and fuel gas metering systems. This template encompasses individual uncertainties' contribution of all the parameters and measurements involved in the volume determination.

Having an expanded uncertainty with respectives contributers allows to define all areas for improvements opportunities. We know now where uncertainty can be improved and recommendations on both equipments and praticies for specific contributors have been identified.

All the approach follows a quality management approach aiming at referencing all information (data, hypothesis). All is well tracked and recorded. Consequently the GHG volume reporting is on the way to be auditable.

This virtuous circle allows continuous improvement and collective awareness. Thanks to this project, the TotalEnergies' approach for GHG volume calculation is evolving in such a way, that we are converging towards the same level of requirements than for oil & gas custody transfer metering systems.

Beyond the quantitative results, this project has acted as a catalyst to capitalize on this critical topic by identifying the good practices, and by defining the actions to be implemented to bring all our facilities up to the same required standards.

6. REFERENCES

[1] ISO/IEC Guide 98-3, Guide to the expression of uncertainty in measurement.