North Sea Flow Measurement Workshop
22-25 October 2019

Technical Paper

The Generic Way to Establish the True Statement about the Uncertainty of Facilities for MPFM/WGFM Validation

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1. ABSTRACT

Over the years, multiphase and wet gas flow metering technologies (MPFM/WGFM) have been improving in terms of reliability and compactness. Lately, with a significant cost reduction, they are planned to be deployed on each wellhead over the coming years. Furthermore, some significant improvements to the measurement uncertainties have been achieved. It is not unusual to now see claims within a few percent on gas or liquid or hydrocarbon flowrate measurements.

This significant effort, based on understanding the fluid mechanics, sensor technologies, and modelling, should be recognized. An immediate consequence is the need to ensure that the claimed performances are correct, fair and can be checked against very high-quality references (i.e., low uncertainty). Today with 100million BOPD with a value of $6Bn per day, an error of 0.1% leads to more than $2Bn revenue per year, which can be a gain or loss during the trading among the partners.

At this date, the best way to verify multiphase and wet gas metering technologies is by testing at multiphase and wet gas reference facilities, where the standard states that the overall facility uncertainty should be 3 to 4 times better than the MPFM/WGFM (i.e., within 0.5% to 1%).

Establishing the overall facility uncertainty should be straight forward as soon as the procedures to identify the entire chain of errors are well understood and considered and evaluated in a fair manner. In case of doubt, the highest uncertainty value should be systematically considered (most pessimistic case until proper evaluation and proven justification have been made). Additionally, the overall uncertainty of the third-party ones, which are technically independent and impartial, should be publicly available for review to all the stakeholders testing or validating MPFM/WGFM performance for a proper understanding of the challenges, and not hidden as it is today.

The purpose of this paper is to show that the process to establishing the overall facility uncertainty should be identical because all these facilities are based on the same principle with a separator, single-phase pumping process through some reference flowmeters, and after mixing them and passing through the MPFM/WGFM, back to the separator. Additionally, the calculation from line to standard conditions should be following the same generic way from reference measurement to multiphase flowmeter conditions and then to standard conditions.

This paper will address how to establish the process to use to take all the measurements and phenomena into account, and how all these facilities could be comparable for the manufacturers or the future end-user expecting to verify the actual performance of the MPFM/WGFM. This shared understanding will be beneficial for the entire multiphase and wet gas metering community and help

everybody to understand the true flowmeter performances and the final expectations. This comprehensive way will be essential for oil and gas companies that can be exposed to significant financial loss through the business of allocation, tieback, custody transfer, or fiscal metering.

2. INTRODUCTION

Multiphase and wet gas facilities have been designed to simulate the three-phase flow of oil, water, and gas production, and to test and evaluate the new flow metering technologies. The facilities are, in a generic way, around a three-phase separator that contains the working bulk of oil and water, including gas for most of them. To be more representative of the field conditions, the multiphase and wet gas facilities should be using at least salty water, and either refined or crude oil following the type of expected testing, as described later. Following the care about safety reasons, the gas could be either inert gas or natural gas, which will have an impact on the overall uncertainty statement. It should be noted that none of the facilities around the world can today mimic the field conditions accurately; this is due to the significant variation of field conditions, pressure, and temperature conditions.

Lately, we have seen the gas business growing much quicker than the whole business; for such specific wet gas facilities, we should anticipate that the water will be either freshwater or salty water following the type of stimulation expected. The former choice will represent condensed water coming from the gas phase by a significant change of pressure and temperature from the reservoir to surface conditions. The latter case is representing the formation of water coming from the reservoir to the surface (water coning).

This document will detail the uncertainty calculation methodology of the reference volumetric flowrates that the facilities should be considering and demonstrating how to calculate these reference flowrates correctly at the device under test (DUT) conditions. The review of all the relevant uncertainty sources and contributions will be explained generically, and this document will try to support with some pieces of evidence some statement about the uncertainty claims that should be included within the uncertainty budget for any given third-party test facility. It is an attempt to document best practices on “how to calculate uncertainty properly on third-party facilities”.

3. TYPICAL LAYOUT FACILITY

A multiphase or wet gas facility is based around a three-phase separator which contains the working bulk fluids. Oil, water, and gas are circulating inside the pipe using pumps and blowers for most of the cases. If the contrast of density between the liquid and gas is substantial, in most of the cases, we should anticipate the opposite between the oil and the water phases. In such cases we need to ensure that the size of the separator is large enough, or there is a multiple-stage separation process in order to ensure that there is none (ideal case) or minimum contamination of the oil by the water or water within the oil; and in the same manner, but more comfortable to achieve, little to no liquid or carrying over through the gas line. As an immediate statement, each outlet line from the separator shall contain a monitoring device to look at the level of contamination and therefore be able to correct the reference flowrates of each phase adequately. With a recirculation of the fluid, heat exchangers to stabilize the temperature are necessary.

The separator is the critical element of such certification or validation facilities. It will be very beneficial for the high-end facility to have what we call double-flow measurement references. This will allow in real-time to verify any deviation or drift of a given single-phase reference flowmeter against the other one or to establish a contamination level immediately on one of the single-phase lines (figure 1).

The type of single-phase reference flowmeters is, in general, orifice plate, Coriolis, Venturi, turbine flowmeter, ultrasonic flowmeter, or sonic nozzles. In general, the cross-contamination monitoring devices are either Coriolis or densitometer; in any case, the contamination should be measured continuously, and verified by regular sampling with offline analysis.

For accurate volumetric gas flow measurement, it is necessary to correct for the expansion of the gas through the measurement of the temperature and pressure of the gas along the pipe. This should be done at different places, first at the reference measurement point; second, as a recommendation, at the inlet of the DUT; third, at the multiphase or wet gas test section of the DUT; fourth, as a recommendation, downstream of the DUT. The benefit is not only to be able to calculate gas flowrate at different points but also to verify that all equipment is working correctly and be able to establish the total pressure loss through the DUT, which is the critical parameter for production engineers.

Reference flowrates to be provided by the facility shall have the highest level of quality, they should be calibrated against accurate standards, and on facilities maintaining traceable primary calibration facilities, or audited by experts from, for example, National Measurement Institute (NMI), if they are not themselves primary calibration certified. Calibrations records of all reference devices should be maintained over the years, and the longer the track record, the better the estimation of the uncertainty associated with the drift. As we will demonstrate later, any equipment has a drift in measurement output, and this one needs to be estimated and considering in the overall budget of the uncertainties.

In any case, to provide the high gas quality of measurement, and therefore the lowest uncertainty claim, flowmeters should be traceable to primary standards. Still too often, we have seen that the claim coming from the manufacturer of the single-phase flowmeter was used as the global uncertainty of the references. Numerous papers have been published over the last years that Coriolis flowmeters, for example, are dependent on the pressure or Reynolds number, this is unlikely taken into account specifically for the third party facility inside the single-phase flowmeters, most of the time it is a generic correction that has been proposed and may not meet at all the expectation in terms of uncertainty for such device. It was also seen that the uncertainty claim given related to the reference location and not at the DUT conditions, we hope that the next sections of this paper will demonstrate that such a statement should not be made.

Finally, the uncertainty in multiphase and wet gas flow measurement has been agreed to be made with a 95% confidence interval or said, in other words, a K-factor equal to 1.96.

Note: Often, we see the K-factor equal to 2; this is still surprising for the authors because it is introducing an extra uncertainty of 2% unnecessarily on the final claim.

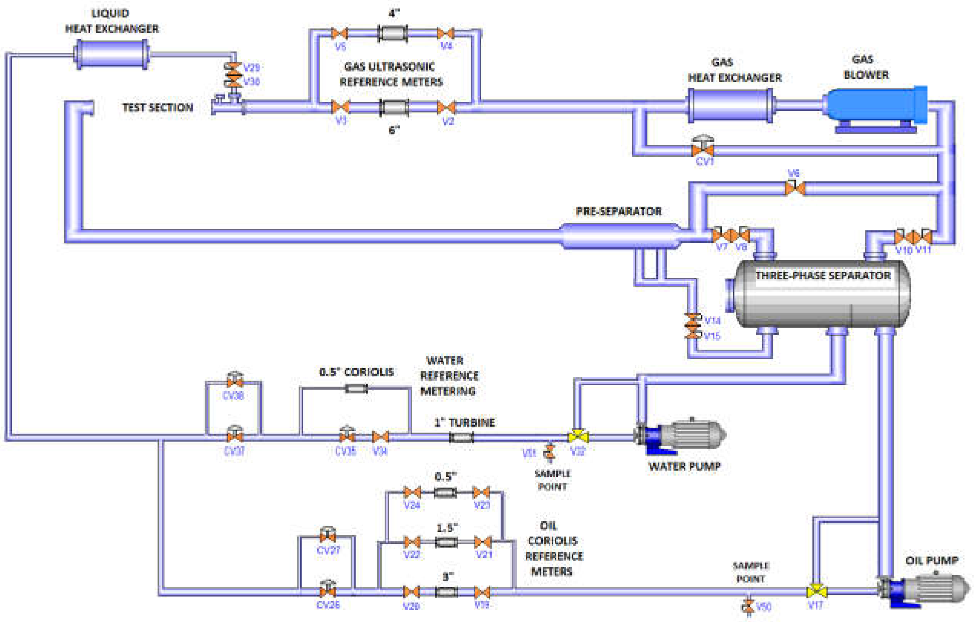


Figure 1: Typical multiphase facility, using Coriolis, turbine, and ultrasonic single-phase flowmeters following the type of fluid.

4. INTRODUCTION TO UNCERTAINTY

The uncertainty of measurement indicates the quality of the present measurement, and 3 numbers need to be specified:

- The actual value of the measurement of the quantity recorded (usually in the right of multiple measurements);
- The associated measurement of the uncertainty (which is associated with the standard deviation on the recorded measurements for the least);
- The level of confidence and the K factor, which in this case should be addressing 95% confidence interval.

The analyses of the measurement uncertainty can be reduced to a simple step-by-step procedure as presented below:

- Define the relationship between all the input parameters or measurements and the final output measurement;
- For each input parameter established, a list of all the factors that can contribute to the uncertainty;
- For each uncertainty source identified, estimate the magnitude of the uncertainty. In case of any doubt, the estimation should take the most pessimistic case;

- Combine all the input uncertainties to obtain the overall uncertainty for the output measurement
- Express the overall uncertainty within, in our case, a 95% confidence interval, which defines the range where the expected new output measurement will be.
- Express the overall uncertainty on the average measurement value, which, as seen later, is associated with the duration of the recording and the acquisition frequency.

The guide to the expression of uncertainty in measurement (Ref [6]) is notifying the way to proceed to the calculation of the uncertainty. There are two recognized basic approaches to analyze the uncertainty of a system. The first is the analyze of the statistical data (defined as type A). For type A analysis, a fair amount of data is collected, and then statistical claim on the deviation is calculated. The second approach (type B), is a non-statistical assessment, and it is based on experience and expected professional judgment to establish a numerical limit on the uncertainty of this quantity, as indicated earlier the most pessimistic case should be used.

In the multiphase and wet gas flow businesses, many variables or output parameters are calculated; however, most of them are based on some primary measurements, and therefore the uncertainty associated with these parameters should be calculated using the typical propagation of error based on the so-called root mean square deviation techniques.

4.1. Analysis of statistical data

As mentioned above, a series of measurement is made and then it is easy to establish the mean of the value as presented below:

$$< z >= \frac{1}{n}\sum z_i \qquad (1)$$

It is also easy to establish the uncertainty associated with this value by calculating the standard deviation as presented below:

$$S(z) = \sqrt{\frac{\sum_i \left(z_i - < z >\right)^2}{n-1}} \qquad (2)$$

It should be evident that the value given with the formula above is not telling that the exact measurement is between these two values ($< z > -k.S(z); < z > +k.S(z)$), but if another measurement is made there is 95% chance that the value will be within this range. To establish the uncertainty on the mean value and therefore stating where should be the true value, the following formula should be used:

$$S(< Z >) = \sqrt{\frac{\sum_i \left(z_i - < z >\right)^2}{n.(n-1)}} \qquad (3)$$

As expressed above, the multiphase and wet gas businesses are claiming expanded uncertainty (usually called "U") within a 95% confidence interval; in such cases, a "k" factor should be used, and it is equal to 1.96. This is representing the expanded uncertainty $U_Z = k.u_Z$.

4.2. Uncertainty Estimation

As mentioned above, combining uncertainty is not using arithmetic sum but the techniques known as Root Mean Square Deviation. The absolute uncertainty for the sum or the difference between the two parameters is given by:

$$z = x + y \text{ or } z = x - y \text{ by } u_Z = u(z) = \sqrt{u^2(x) + u^2(y)} \qquad (4)$$

The relative uncertainty for the product of parameters or division of parameters $z = x / y$ or $z = x.y$ is given by:

$$\frac{u(z)}{z} = \sqrt{\frac{u^2(x)}{x^2} + \frac{u^2(y)}{y^2}} = \sqrt{\left(\frac{u(x)}{x}\right)^2 + \left(\frac{u(y)}{y}\right)^2} \qquad (5)$$

Earlier, we have been using the extended uncertainty with a k=1.96. However, this value is applicable if the distribution is following Gaussian or a Normal distribution or bell-shaped curve. The final uncertainty about the mean measurement follows a normal distribution. The case of a non-normal distribution leads to the use of different K factors. For example, in the case of a rectangular distribution, the K factor is 1.73 (√3). Examples of rectangular distribution cases are sensor readings, drift, fitting equation.

Although most situations will comply with Normal or Rectangular distribution, there are some others to know, especially if some clippings are involved. The U-shaped distribution is based on a function that represents outcomes that are most likely to occur at the extremes of the range. The distribution forms the shape of the letter 'U,' but does not necessarily have to be symmetrical. As an example, consider the thermostat that controls the temperature of a room. If you are not using a PID controller, your thermostat controller only attempts to control temperature by activating at the extremes, and the K-factor is 1.41 (√2). The triangle distribution is a function that represents a known minimum, maximum, and estimated central value. It is commonly referred to as the "lack of knowledge" distribution because it is typically used where a relationship between variables is unknown. Imagine the controlled temperatures inside a room which is continually floating around the set value and rarely reach the temperature thresholds (i.e., limits) of a typical thermostat controller. The K-factor is 2.45 (√6) in this case. What this means is that most of room's temperature data is centered around the set temperature. Some other types of distribution are existing, and they have a different K-factors, but they are quite uncommon in our flow metering systems.

4.3. Sensitivity Coefficients Calculation

Each parameter involved inside the calculation of the overall uncertainty may have a different impact or sensitivity, to establish this dependency, the calculation of the sensitivity coefficient is necessary. The technique of the partial derivative is used in this case, as presented here below:

If $z = fn(x, y)$ and x and y are not correlated then:

$$u_Z = u(z) = \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 .u^2(x) + \left(\frac{\partial z}{\partial x}\right)^2 .u^2(y)} \qquad (6)$$

The sensitivity coefficients such as described above by $\left(\frac{\partial z}{\partial x}\right)$ or $\left(\frac{\partial z}{\partial y}\right)$ are a measurement of the impact of the uncertainty from the inputs parameters on the overall uncertainty, and they can be found either by analytical analyses as presented above or by numerical analyses (typically a Monte Carlo simulation).

4.4. Common Uncertainty

There are only a few prevailing uncertainties that should be notified to establish the overall uncertainty associated with the multiphase or wet gas third-party test facility. The four main ones are:

1) Calibration uncertainty,
2) Equation fit uncertainty,
3) Drift uncertainty,
4) Uncertainty about the mean measurement.

Each of them will be described below. In some cases, additional sources of error can exist, but there are usually not significant in the overall statement of the uncertainty.

4.4.1. Calibration Uncertainty

Calibration uncertainty is the uncertainty of the calibration process transferred to the new instrument; in other words, the uncertainty of the new instrument could never be better than the one used to calibrate. This makes primary calibration facilities way different from secondary or other types of facilities. To be able to maintain such a level of uncertainty at the lower possible value, a large amount of money, techniques are used.

It is quite common, for example, to calibrate turbine flowmeters against sonic nozzles; liquid single-phase flowmeters will be calibrated against either prover or gravimetric system, which leads to uncertainty usually below ±0.05% in most of the cases.

4.4.2. Equation Fit Uncertainty

Due to time constraints, the calibration of a reference flowmeter is done across some given flow range. This means that interpolation will be required between the different measurements made on the primary calibration facility. A fitting algorithm is applied in such cases, and this will define the characteristics of this flowmeter across the full range of flowrates covered during the calibration. This fitting curve could be linear in some cases, but most of the cases it is non-linear, and in such cases it is quite indispensable to have enough data to provide a proper fit equation. If it is impossible to establish a linear equation, then a polynomial fit should be used with as recommendation that the degree of this polynomial fit should be kept as low as possible by doing some trial tests. It should be interesting to note that the uncertainty in the equation fit for a particular instrument is likely to change when a new calibration is made, and therefore the uncertainty budget must be updated periodically to reflect these changes.

Figure 2 presents a non-linear behavior for a gas flowmeter; the two red lines are showing the 95% confidence interval around the curve fitting. A relative uncertainty of ±0.10% could be a reasonable target and could be improved if enough data were recorded and probably reaching a target within ±0.05%. Figure 2 below shows a case where the uncertainty is within ±0.4%.

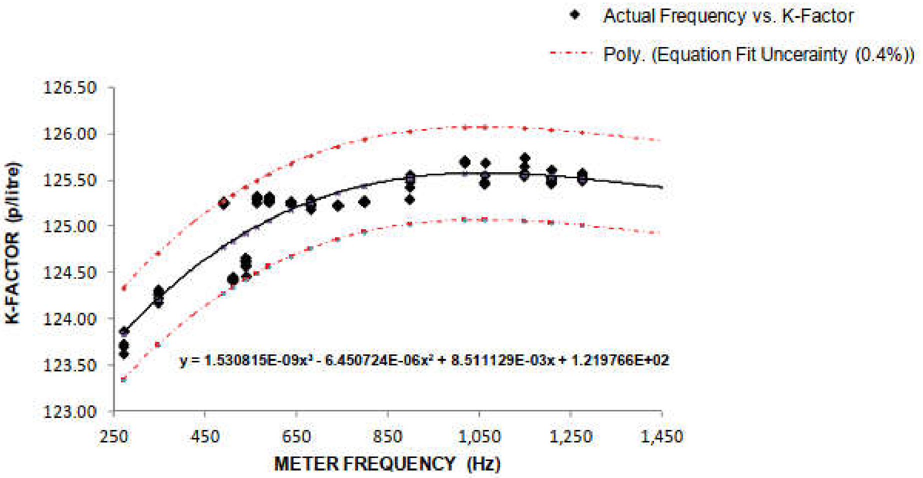


Figure 2: A typical Curve Fitting Calibration with the associated 95% uncertainty range (±0.4%)

4.4.3. Drift Uncertainty

As indicated earlier, reference single-phase flowmeters should be calibrated at least annually against primary calibration devices; however, drift in the measurement in the period between two calibrations should be expected over time. This uncertainty is coming from the fact that the equation fit may not be entirely representative throughout the period (i.e., yearly). If no historical data are available, it is impossible to obtain an uncertainty figure for the drift. In this case, an engineering judgment or based on experience with similar devices should be provided, and an uncertainty figure should be estimated. With enough historical data available a target of ±0.10% should be achievable.

Figure 3 below is showing historical data in the calculated K-factor for the turbine flowmeter at different years. It can be seen in the year-on-year calibration that the flowmeter is within ±0.25% with a 95% confidence level. In this specific case, the functioning pressure and temperature ranges for this flowmeter have been evaluated during the calibration, and therefore the pressure and temperature effects are included in the drift value stated. If this was not the case, an additional uncertainty associated with the pressure and temperature should be considered.

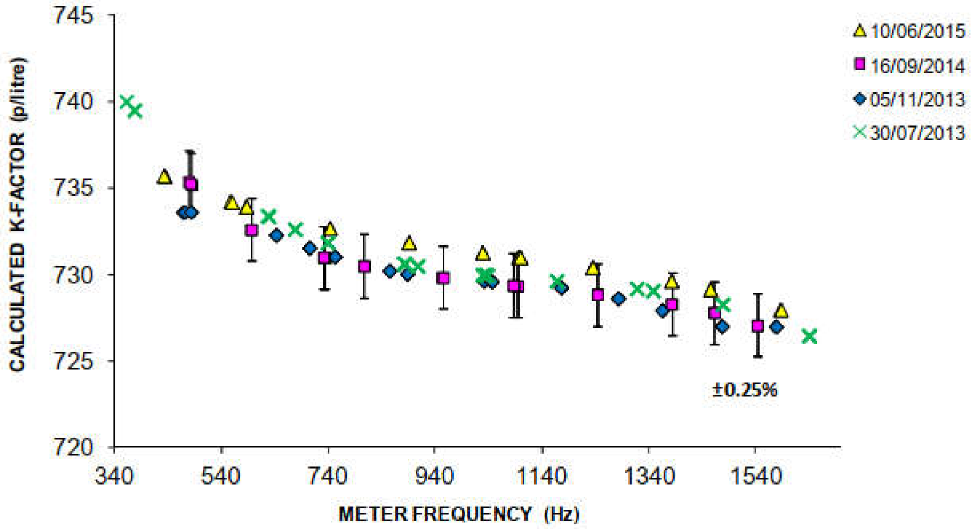


Figure 3: A typical drift uncertainty over two years for the K factor of the turbine flowmeter

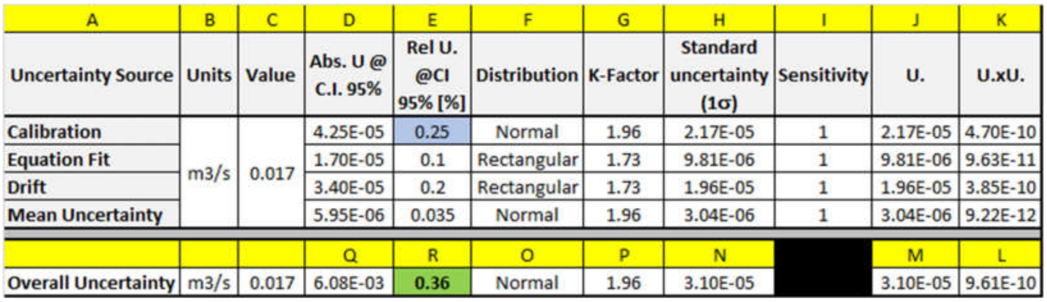
4.4.4. Uncertainty about the mean measurement

What we mean by uncertainty about the mean measurement is the fact that different conditions will be recording on the facility, and we will be using the correct K-factor to ensure that the coefficient to applied is the right one and the normality of the distribution should be reviewed. Different techniques can be used to get this normality validity; we could look at the skewness and the Kurtosis of the distribution. The uncertainty about the mean is calculated statistically from the standard deviation and the actual test for each instrument recording data, which are used to evaluate the final reference flowrates corrected to DUT conditions.

4.5. Example of Combining Uncertainty

At this stage we have been producing all different primary types of uncertainties, it is essential now to realize that all the sources of uncertainty will not be at their extreme value simultaneously and if simply the sum of the input uncertainties were directly used, this would give an overly pessimistic statement. To recognize the fact that the uncertainties are uncorrelated, the technique of the root mean square deviation is used. This is a typical type of equation that is used inside the table presented here below. This is the standard type of presentation used at the national engineering laboratory (NEL) to establish the overall uncertainty.

Let's take the example of the single-phase gas flowmeter reference measurement, and let's see how the propagation of error develops, considering the calibration uncertainty, the uncertainty of fitting equation, the drift uncertainty, and as said earlier the uncertainty about the mean measurement (C column). We build the table by inserting the relative uncertainty values (E column) in percentage from both values capable of establishing the absolute uncertainty (D column). We need now to understand what types of distribution that we are facing; is it a normal distribution or rectangular distribution (Column F), defining distribution will give us access to the K factor (Column G) used to establish the uncertainty which is a value with one Sigma or one standard deviation (Column H). The sensitivity factor is assuming for the specific case to equal to 1 (Column I), and this will calculate the uncertainty of each value (Column J). We can now square the uncertainty (Column K), and we can sum them up (cell L). The uncertainty can be obtained by taking the square root (Cell M and N), now it is possible to calculate the relative uncertainty by assuming it is a normal distribution (Cell R) which will always be the case the relative uncertainty leading to a value of ±0.36%. It is interesting to compare this value with the initial calibration of the single-phase flowmeter value, which was ±0.25%.



A	B	C	D	E	F	G	H	I	J	K
Uncertainty Source	Units	Value	Abs. U @ C.I. 95%	Rel U. @CI 95% [%]	Distribution	K-Factor	Standard uncertainty (1σ)	Sensitivity	U.	U.xU.
Calibration	m3/s	0.017	4.25E-05	0.25	Normal	1.96	2.17E-05	1	2.17E-05	4.70E-10
Equation Fit			1.70E-05	0.1	Rectangular	1.73	9.81E-06	1	9.81E-06	9.63E-11
Drift			3.40E-05	0.2	Rectangular	1.73	1.96E-05	1	1.96E-05	3.85E-10
Mean Uncertainty			5.95E-06	0.035	Normal	1.96	3.04E-06	1	3.04E-06	9.22E-12
			Q	R	O	P	N		M	L
Overall Uncertainty	m3/s	0.017	6.08E-03	0.36	Normal	1.96	3.10E-05		3.10E-05	9.61E-10

The letters show the sequential way to fill up the table with: C the reading value, D the extended uncertainty at C.I 95%; E=D/C; G Boolean following the type of distribution from F, H=D/G, J=H*I, K=H*H, L=sum(K:K), M=Sqrt(L); N=M; Q=P*N; E=Q/B

Table 1: Uncertainty Budget for a Gas Reference Turbine and the process to follow in alphabetic order from A to R

Such a presentation in table 1 allows immediately to get a full picture of the overall uncertainty and to focus on the most significant uncertainty sources to reduce the overall uncertainty (primarily looking at column K). The input uncertainty sources can, therefore, be ranked to determine which sources are having the most potent effect on the overall uncertainty.

5. COMBINING UNCERTAINTY FOR FLOWRATES AND DENSITIES

At this stage, we have shown how to calculate the uncertainty for a given single-phase flow measurement, but in the context of the multiphase and wet gas facilities; there are principally six measurements to provide which are respectively oil, water, and gas flowrates; and oil, water, and gas densities.
In the next sections, we will look at the gas density uncertainty associated with pressure and temperature measurement uncertainty, but also considering the atmospheric pressure uncertainty. Later, we will look at the oil and the water flowrate measurement uncertainty.

5.1. Modeling of the Gas Density

Probably one of the main challenges in the calculation of uncertainty will be the one associated with the gas density; effectively, the gas density is depending strongly on pressure measurement and slightly less dependent on temperature. Whatever type of gas that is used in this multiphase or wet gas facility, the modeling of the gas density versus pressure and temperature is necessary. In the case of the use of natural gas an additional dependency versus the gas composition will also be quite significant. In this example, below, we show already all the challenges associated with inert gas. The following equation can express the density of the gas:

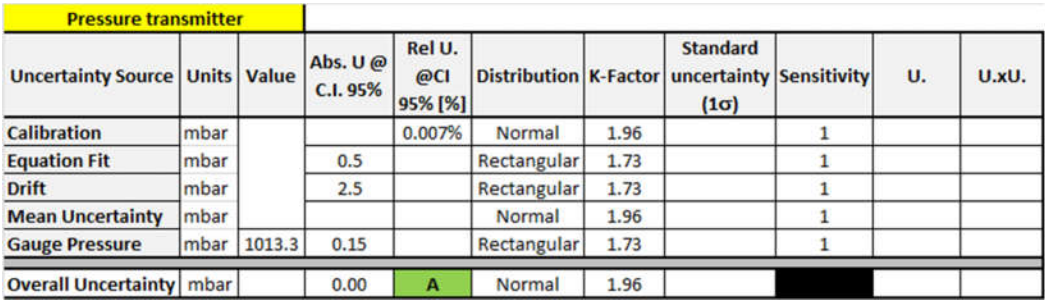
$$\rho_{N_2} = \frac{P_{@lc[Pa]}}{Z}\frac{R}{T_{@lc[K]}} = \frac{1}{Z}\frac{T_{@sc[K]}}{T_{@lc[K]}}\frac{P_{@lc[Pa]}}{P_{@sc[Pa]}} \qquad (7)$$

Z is representing the compressibility factor; the temperature should be in Kelvin and the pressure should be in Pascal (or bara), with R the specific gas with a unit in J/kg.K. The uncertainty value of gas density calculated from the above equation for Nitrogen was leading to ± 0.02% in the appropriate range of line pressure and temperature investigated by NEL.

5.2. Gas Pressure Measurement Uncertainty

The modeling of the gas density, as indicated, is calling for the pressure and temperature measurement; it is, therefore, necessary to get access to the uncertainty on both parameters. As presented before, the pressure measurement uncertainty will be associated with calibration uncertainty, the equation fit uncertainty, the drift uncertainty, but also with the atmospheric pressure measurement uncertainty. As a reminder, readings taken from pressure transmitters indicate gauge pressure, and it is converted into absolute pressures for use in the governing equation by the addition of the absolute atmospheric pressure, commonly taken as equal to 1.01325 bar. This is an approximation, and a proper evaluation should be done. Indeed, usually the test on any of these facilities will go from few days to few weeks and if the standard atmospheric pressure was used instead of measured values then absolute pressures calculated will be inaccurate. The uncertainty of the absolute pressure calculation will directly impact the uncertainty in gas density calculation. Obviously, this is irrelevant if the facility is inside a building or outside. The authors have not seen today any facility where the pressure inside a building was controlled and kept constant. NEL has been doing some tests and discovered that the uncertainty in using the standard atmospheric pressure could lead to ±4.2% error. As an outcome of this research program, atmospheric pressure is measured directly and continuously during the test.

We are now using a second device to calculate the absolute pressure and, therefore, will need to consider the calibration uncertainty associated with this parameter; the uncertainty in the calibration process has been determined to be within ±0.15 mbar with a 95% confidence level. The table here below summarises all the input parameters currently available:

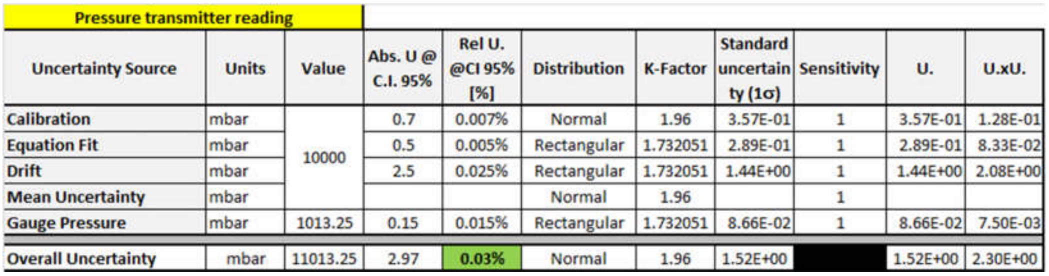


Pressure transmitter

Uncertainty Source	Units	Value	Abs. U @ C.I. 95%	Rel U. @CI 95% [%]	Distribution	K-Factor	Standard uncertainty (1σ)	Sensitivity	U.	U.xU.
Calibration	mbar			0.007%	Normal	1.96		1		
Equation Fit	mbar		0.5		Rectangular	1.73		1		
Drift	mbar		2.5		Rectangular	1.73		1		
Mean Uncertainty	mbar				Normal	1.96		1		
Gauge Pressure	mbar	1013.3	0.15		Rectangular	1.73		1		
Overall Uncertainty	mbar		0.00	A	Normal	1.96				

Table 2: Uncertainty Budget for an Absolute Pressure Measurement

It is quite interesting to note that if we imagine the value around 10 bar then the absolute uncertainty on the reading based on the calibration will be around ±0.7 mbar as presented in the table above, however taking into account the different uncertainties, the overall uncertainty is much higher and the one, in this case, associated with the drift is the most predominant one. It needs to be considered not only ±0.7mbar but also ±0.5mbar, ±2.5mbar, and finally ±0.15mbar, as a minimum. This leads to the following table with 10 bara line pressure reading and overall uncertainty, without considering the possible uncertainty on the mean value, of 0.03% (a factor 4 larger than anticipated for the least!):



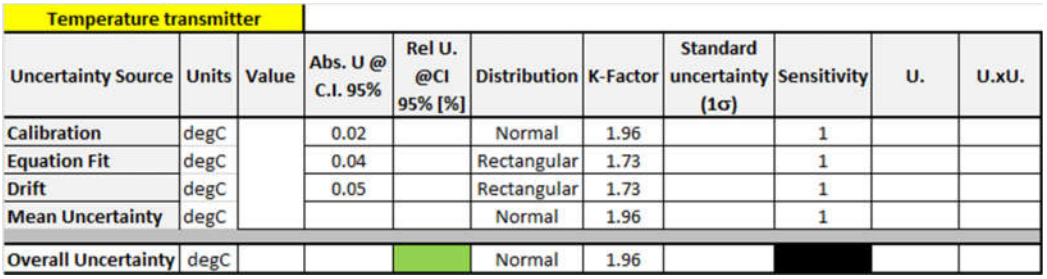
Pressure transmitter reading

Uncertainty Source	Units	Value	Abs. U @ C.I. 95%	Rel U. @CI 95% [%]	Distribution	K-Factor	Standard uncertainty (1σ)	Sensitivity	U.	U.xU.
Calibration	mbar	10000	0.7	0.007%	Normal	1.96	3.57E-01	1	3.57E-01	1.28E-01
Equation Fit	mbar		0.5	0.005%	Rectangular	1.732051	2.89E-01	1	2.89E-01	8.33E-02
Drift	mbar		2.5	0.025%	Rectangular	1.732051	1.44E+00	1	1.44E+00	2.08E+00
Mean Uncertainty	mbar				Normal	1.96		1		
Gauge Pressure	mbar	1013.25	0.15	0.015%	Rectangular	1.732051	8.66E-02	1	8.66E-02	7.50E-03
Overall Uncertainty	mbar	11013.25	2.97	0.03%	Normal	1.96	1.52E+00		1.52E+00	2.30E+00

Table 3: Uncertainty Budget for an Absolute Pressure Measurement of 10 bara (with A =0.03%)

5.3. Gas Temperature Measurement Uncertainty

The overall uncertainty for the temperature measurement depends again on the same parameters, i.e., calibration, equation fitting, drift, and mean uncertainty. Table 3, below, summarizes the different information as collected. As indicated with the pressure transmitter we have the same phenomena for the temperature transmitter where the calibration is excellent however there are associated uncertainties with the fitted equation and the drift, and this needs to be considered, even if they are small, they are, in general twice higher than the calibration uncertainty.

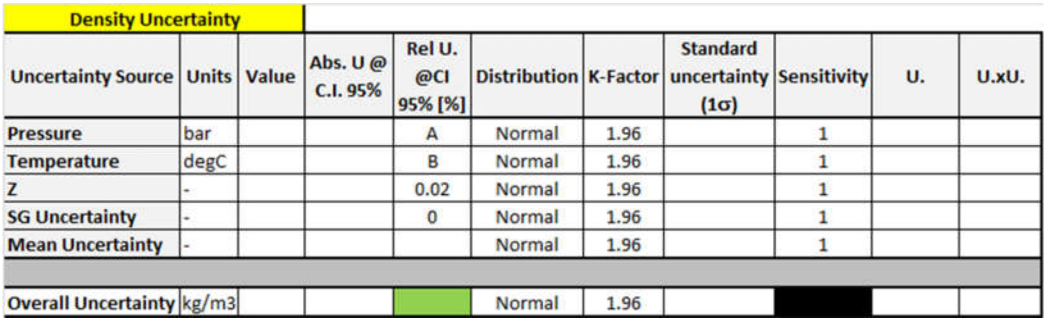


Temperature transmitter

Uncertainty Source	Units	Value	Abs. U @ C.I. 95%	Rel U. @CI 95% [%]	Distribution	K-Factor	Standard uncertainty (1σ)	Sensitivity	U.	U.xU.
Calibration	degC		0.02		Normal	1.96		1		
Equation Fit	degC		0.04		Rectangular	1.73		1		
Drift	degC		0.05		Rectangular	1.73		1		
Mean Uncertainty	degC				Normal	1.96		1		
Overall Uncertainty	degC				Normal	1.96				

Table 4: Uncertainty Budget for a Temperature Transmitter

Based on the uncertainty for the different elements presented in the section above, it is now possible to establish overall uncertainty of the density as presented in the table here below:



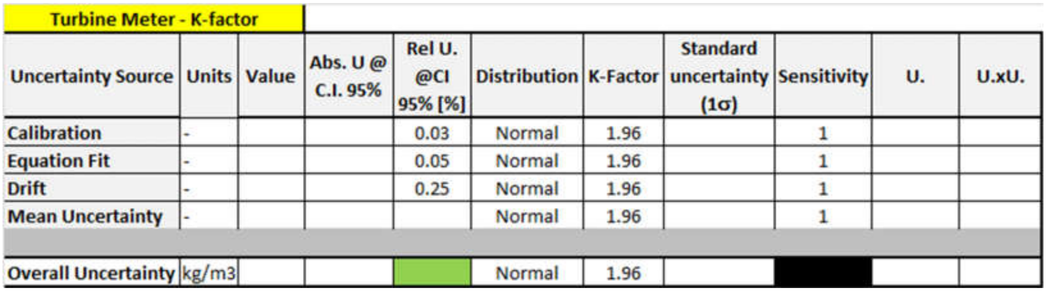
Density Uncertainty										
Uncertainty Source	Units	Value	Abs. U @ C.I. 95%	Rel U. @CI 95% [%]	Distribution	K-Factor	Standard uncertainty (1σ)	Sensitivity	U.	U.xU.
Pressure	bar			A	Normal	1.96		1		
Temperature	degC			B	Normal	1.96		1		
Z	-			0.02	Normal	1.96		1		
SG Uncertainty	-			0	Normal	1.96		1		
Mean Uncertainty	-				Normal	1.96		1		
Overall Uncertainty	kg/m3			🟩	Normal	1.96		⬛		

Table 5: Uncertainty Budget for a Gas Density the value of A and B should come from the above analysis and are not representing at all the calibration uncertainty but a value 2 to 3 times higher in general.

It should be noted that the uncertainty associated with the specific gravity is in this case of an inert gas like nitrogen and the uncertainty on Z of ±0.02% obviously will not be the case if life gas or natural gas are used because this number needs to be changed adequately to the composition. Another important statement is that if the specific gravity is associated with the composition, which needs to be accurately described, but also ensures that the sample taken was representative of the flowing fluid as a free gas inside the pipe. Consequently, it should be noted that the dissolution of the gas inside the oil or the water will not be equivalent to the free gas composition. Indeed, the solubility of some components (i.e., C1, C2, C3…., CO2, H2S, N2) is better than the other. It is then imperative to take a sample after stabilization of the entire fluid in the facility, after some recirculation to ensure the entire fluid is at a stable stage (this is to address the representativity) and to use gas chromatography as much as possible during the test (best solution will be a continuous measurement, this is to address the uncertainty).

5.4. Modeling of the Oil or Water Turbine flowmeter

The measurement of the oil and water flowrates can be achieved with multiple types of single-phase flowmeters; in this section and as an exercise, it was decided to use a turbine flowmeter, which we could imagine to be quite simple to use. As known now, it is necessary to establish first the calibration uncertainty, then the uncertainty associated with equation fit, then with the drift and the mean uncertainty. Calibration uncertainty against some national standard primary references could lead to a value within ±0.03%. However, we need to be careful about the fluid property that may change over time due to the contamination or degradation. The fluid properties of the pure oil and the water should be reviewed routinely to minimize drift uncertainty in fluid density, for example. A possible good indicator with the density could be, for example, the kinetic viscosity. The equation for uncertainty is usually linked with such devices, with a K factor that needs to be developed for the entire range of viscosity and leads to value for the specific cases around plus ±0.05% with a 95% confidence interval. The drift uncertainty needs to be established over multiple calibrations in time, and it can be established to be around plus ±0.25% with a 95% confidence interval. As mentioned before, the long track record with the turbine flowmeters, which means calibration with different oil and, therefore, viscosity and different types of pressure will include the drift associated with these parameters. Again, it can be noted that the calibration uncertainty was minimal but considering all the sources of uncertainty the final statement about the overall uncertainty is significantly different.



Turbine Meter - K-factor

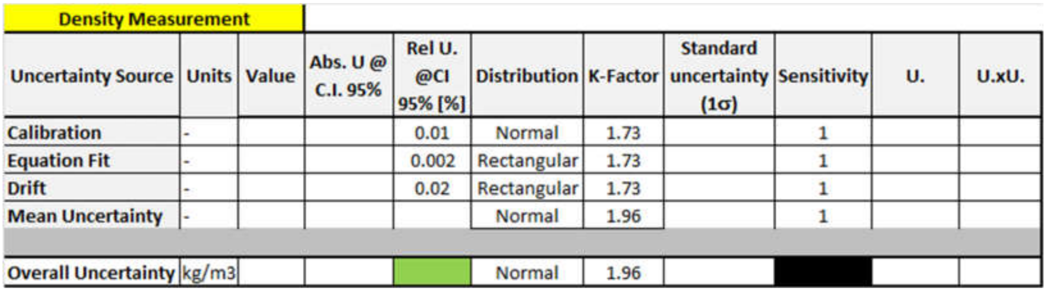
Uncertainty Source	Units	Value	Abs. U @ C.I. 95%	Rel U. @CI 95% [%]	Distribution	K-Factor	Standard uncertainty (1σ)	Sensitivity	U.	U.xU.
Calibration	-			0.03	Normal	1.96		1		
Equation Fit	-			0.05	Normal	1.96		1		
Drift	-			0.25	Normal	1.96		1		
Mean Uncertainty	-				Normal	1.96		1		
Overall Uncertainty	kg/m3			🟩	Normal	1.96		⬛		

Table 6: Typical Input Data for the Uncertainty Budget of a Turbine K-Factor

5.5. Oil or Water Density Measurement

To establish the density of each liquid phase, it is necessary to apply the same procedure as presented above and, therefore, to establish the uncertainty associated with the temperature transmitter set online, for example, but also pressure in case of gas dissolution, or live oil. It is precisely the same type of process established for the gas density and the associated temperature and pressure sensor that should be developed. The value of the uncertainty may be slightly different for each reference temperature and pressure transmitter, and this needs to be checked carefully.

For the measurement of the density, a precise measurement could be achieved with, for example, an Anton Paar device for the reference measurements, which has an uncertainty of ±0.01%. The typical process with the uncertainty associated with the fit equation, drift, etc should be studied. This will lead to such type of overall uncertainty table as presented here below (Table 7). It should be noted in the case of live fluid (i.e. gas dissolution) that the dependency on the pressure, and therefore additional correction based on composition pressure solubility should be applied for the user to calculate density accurately at reference flowmeter conditions. The salinity will probably change with time, and this should be considered if possible, a real-time measurement better than a sampling time to time.



Density Measurement

Uncertainty Source	Units	Value	Abs. U @ C.I. 95%	Rel U. @CI 95% [%]	Distribution	K-Factor	Standard uncertainty (1σ)	Sensitivity	U.	U.xU.
Calibration	-			0.01	Normal	1.73		1		
Equation Fit	-			0.002	Rectangular	1.73		1		
Drift	-			0.02	Rectangular	1.73		1		
Mean Uncertainty	-				Normal	1.96		1		
Overall Uncertainty	kg/m3			🟩	Normal	1.96		⬛		

Table 7: Uncertainty Budget for a dead fluid Density Measurement for live composition, pressure, and temperature should be considered for additional correction.

5.6. Contamination Monitoring for oil or water line

Different equipment could be used to monitor the contamination of either water or oil. A densitometer could be the best option; in some cases, the use of Coriolis flowmeters will be considered as an adequate solution. The calibration process in such a case needs to consider the range of Water Liquid Ratio contamination possible, for example, from 0% to 15%, if the latter value is seen as the maximum contamination of the oil line. The calibrated reference device, in this case, should be based on sample analyses and use of Karl Fisher techniques, which will be able to determine, for example, the reference water content and the reference mixture density.

A table of the uncertainty analysis similar to the one presented hereabove will be established for this case (Table 8). The contamination level will be established by using the mixture density measurement and the recalculated density of oil and water at the same temperature and pressure conditions. The equation to establish contamination is presented here below:

$$WLR_{\text{contamination}} = \frac{\rho_{m@lc} - \rho_{o@lc}}{\rho_{w@lc} - \rho_{o@lc}} \qquad (8)$$

With lc being the line conditions of pressure and temperature

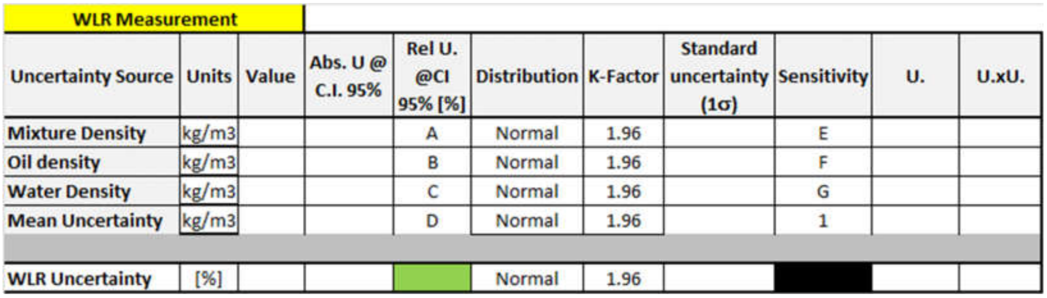
The derivative can be established as presented (formula 9), then the uncertainty on the measurement of the contamination can be produced:

$$\Delta WLR_{\text{contamination}} = \sqrt{\begin{aligned}&\left(\frac{\rho_{m@lc}}{\rho_{w@lc} - \rho_{o@lc}}\right)^2 \left(\frac{\Delta\rho_{m@lc}}{\rho_{m@lc}}\right)^2 + \left(WLR\frac{\rho_{w@lc}}{\rho_{w@lc} - \rho_{o@lc}}\right)^2 \left(\frac{\Delta\rho_{w@lc}}{\rho_{w@lc}}\right)^2 \\ &+ \left((1-WLR)\frac{\rho_{o@lc}}{\left(\rho_{w@lc} - \rho_{o@lc}\right)}\right)^2 \left(\frac{\Delta\rho_{o@lc}}{\rho_{o@lc}}\right)^2\end{aligned}} \qquad (9)$$

To highlight the use of equation (6), we are expressing the sensitivity factor (see for the meaning section 4.3) associated with the oil and water densities uncertainties, and it should be noted that they are WLR dependent.

$$\begin{aligned} E &= \left(\frac{\rho_{w@lc}}{\left(\rho_{w@lc} - \rho_{o@lc}\right)}\right) \\ F &= \left(WLR\frac{\rho_{w@lc}}{\rho_{w@lc} - \rho_{o@lc}}\right) \\ G &= \left((1-WLR)\frac{\rho_{o@lc}}{\left(\rho_{w@lc} - \rho_{o@lc}\right)}\right) \end{aligned} \qquad (10)$$

The summary uncertainty table for WLR can be expressed as follow:



WLR Measurement										
Uncertainty Source	Units	Value	Abs. U @ C.I. 95%	Rel U. @CI 95% [%]	Distribution	K-Factor	Standard uncertainty (1σ)	Sensitivity	U.	U.xU.
Mixture Density	kg/m3			A	Normal	1.96		E		
Oil density	kg/m3			B	Normal	1.96		F		
Water Density	kg/m3			C	Normal	1.96		G		
Mean Uncertainty	kg/m3			D	Normal	1.96		1		
WLR Uncertainty	[%]			🟩	Normal	1.96		■		

Table 8: Uncertainty Budget for WLR contamination based on density measurement either by Coriolis flowmeter or Densitometer

A value is an uncertainty associated with Coriolis reading, and B & C the uncertainty associated the PVT Calculation or densitometer for density of single-phase, and all established from the analysis presented before; D is associated with the fluctuation during the recording time through the standard deviation calculation.

6. EFFECT OF TWO-COMPONENT FLOW ON SINGLE PHASE FLOWMETERS

All single-phase flowmeter technologies have a limitation, and most have a tough time dealing with the two-phase liquid mixtures. Indeed, the characteristics of the liquid-air mixture are extraordinarily complex, and different types of flow patterns may happen following the pressure, the flowrate, and the quantity of the different phases. In our case, we are expecting only contamination, which means a small quantity of gas inside the liquid or in the form of droplets inside the gas line; but even under such conditions the response of the single-phase flowmeter could be very challenging and leading to very high uncertainties, even at low contamination levels.

Over the years, it has been seen or stated that Coriolis flowmeters can handle such conditions. In one of the sections below, we will be focusing on this relative affirmation about the behavior in the presence of a small amount of gas. Authors still believe today that the system capable of providing the best fair uncertainty will be turbine flowmeters as soon as the flow is well mixed.

However, before focussing more on the technology, the first statement is if contamination is measured in the single-phase liquid line, then the response of the flowmeter will no longer be within the calibration specification claimed by the manufacturer. In such a case, a test program should be carried out on this facility to characterize the response and determine the measurement uncertainty due to the two-component flow for the given metering technology. It will be wrong to use the manufacturer statement where they have developed and spend effort to ensure a pure single-phase condition for the flowmeter to ensure the best performance and the lowest achievable uncertainty.

6.1. EFFECT OF TWO COMPONENT MIXTURES ON TURBINE METERS

For example, in the case of the use of turbine flowmeters, it was demonstrated that the magnitude of error is generally within ±0.4% relative to the reference flowrates at the condition of the two-component mixtures. The same type of analysis is done, for example, on the Coriolis flowmeter. The uncertainty associated with the two-component flow effects must be accounted for concerning the level of contamination measured at the reference metering location and flow velocities.

In this approach, the problems resulting from a two-component mixture inside the single-phase line have assumed that no gas was present inside the liquid line; in general, this statement is valid. However, it should be demonstrated for the full range of flowrates claimed on this facility in terms of the gas flowrate versus liquid flowrate. If the separation gas-liquid was not optimal, a significant discrepancy should be expected from the reading of the single-phase liquid flowmeter. There is no mystery, to be able to avoid such type of situation a proper design should be done with either a multistage separation for the gas and liquid or larger separators with if possible a pre-separation stage to facilitate the migration of the gas in the top of the separator and the liquid towards the bottom. Said, in different words, the larger the separator, the better will be the separation between the different phases. NEL is considering that a minimum retention time of five minutes at the full flowrates is a requirement for a closed flow loop.

6.2. EFFECT OF TWO-COMPONENT MIXTURES ON CORIOLIS FLOWMETERS

Coriolis mass flowmeters offer the advantage against the other type of reference meters that two output measurements are provided. One is associated with the mass flowrate and independently the other one associated with the density of the fluid flowing through the Coriolis flowmeter. This has led the industry to use more and more such types of devices, including on the separators liquid and gas lines. Coriolis mass flowmeters are also widely utilized as reference flowmeters in the multiphase and wet gas facilities around the world and are relying intensely on the accuracy of the density measurement to determine the level of oil in water or water in oil cross-contamination.

NEL has been carefully investigating such equipment and developed a facility for high temperature and high pressure to calibrate and determine the effect of these two parameters on the performance of Coriolis flowmeters from 2-inch to larger than a 10-inch diameter. The two main facts about the Coriolis flowmeters are; first, the pressure loss such devices generate are significantly higher than a Venturi tube or an orifice plate. The second fact is that the technology is operating on the vibrating tube principle, and if the oscillation of the tube cannot be maintained then the first action from the Coriolis control system will be to increase the strength of the vibration by increasing the gain until saturation. Today the gain is used as an indicator of some gas flowing through the Coriolis; in simple words, there is significant damping due to the interaction between the gas, which is very compressible, and the fluid, which is slightly compressible or incompressible. This effect is known as the flow tube dumping, and in some cases, the presence of gas will also cause significant variations in frequency and amplitude of the oscillation due to the chaotic nature of the interaction between the gas and liquid.

NEL, among others, have been embracing this technique for reference flow measurement and fluid density measurement for some of the test facilities over the last few years, developing a rigorous approach to account for the known uncertainty sources. In some cases, Coriolis flowmeters are also used as a contamination monitoring device in NEL's multiphase flow facilities.

6.2.1. Large Pressure Loss

Let's first mention the significant pressure loss, which is happening through such mass flowmeter. In the case of inert fluid or with a low solubility versus pressure variation, the effect of the pressure loss will be minimal or said differently, if the pressure loss is let's say 1 to 2 bar, the mass transfer of gas from the dissolution inside the oil, becoming free gas, will be small in terms of volume in this case, and it could be expected that the Coriolis flowmeter will still perform within a fair uncertainty that needs to be established.

In the case of high solubility, or live fluid consider close to volatile high or HIGH GOR2, then a significant release of gas inside the tubing of the Coriolis will happen, and therefore, this will generate the buoyancy concept that we present later.

This is highlighting the challenges which a third party will be facing with fluids having high solubility, and then it will be necessary to increase the overall uncertainty associated with the reference flowmeter where contamination is present. As indicated before, the validity of the measurement needs to be demonstrated, and then a specific program of test needs to be done with the fluids in use in the given facility. In case of a challenge in the establishment of the gas composition or possible change when refill or leaks are happening, the test program needs to be carried out to evaluate the overall uncertainty of the Coriolis flowmeter associated with this significant change. One solution to avoid considerable pressure loss would be to use an oversized Coriolis flowmeter. In this case, the pressure loss will be smaller, but we need to keep in mind that a fair amount of velocity will be necessary through the Coriolis to act and use the Coriolis effect where the meter will be capable of measuring flowrates and the density of the fluid. NEL, through numerous research programs, found that having a velocity above 1m/s is a minimum for optimal Coriolis flowmeter performance.

6.2.2. Two-Phase Response

We have highlighted the challenges associated with the Coriolis flowmeter and the pressure loss through the device. As known, for the user of the Coriolis flowmeter, the setting of this equipment is different following the use in liquid or gas phase applications. In case of possible secondary component contamination in liquid applications, a study of the orientation of the Coriolis flowmeter for best performance in two-component mixtures should be carried out. NEL has been conducting such test programs with the fluids used in the different multiphase facilities and demonstrated that the Coriolis flowmeter should be installed in the vertical orientation with flow upwards through the flowmeter. In addition of the recommendation for installing the Coriolis flowmeter in a vertical configuration, a minimum distance of five diameter after blind tee or bend was established as a best practice in order to ensure a mix of both oil and water in each Coriolis tube and therefore minimize impact on the performance due to a non-uniform fluid mixture inside the tubes. This type of configuration has been adopted for the installation of the Coriolis reference flowmeter on the NEL facilities where they are present. The test program developed by NEL has been using different types of refined oil (Kerosene and Paraflex HT9), but also crude oil from the Forties, Beryl, Oseberg, Ekofisk were included.

It should be kept in mind that the Coriolis manufacturer usually calibrates them in water and at low pressure; unfortunately, for the third-party facilities around the world the pressure will be much higher, and then this could have a significant impact on the performance of the flowmeter. The result from the NEL test program highlighted the importance of performing the calibration of the Coriolis flowmeters in same type of conditions (Pressure and temperature), which will be faced during the service. In other words, the calibration needs to be done at the pressure that the Coriolis will be measuring. NEL's studies have demonstrated that the performance of the Coriolis flowmeter could be different versus line pressure and following the size for the same brand. Figure 4 here below is showing, for example, the use of the Coriolis calibrated by a manufacturer obviously with water, and use on the oil line against a very well established reference density measurement. It can be seen clearly that there is a systematic under reading coming from this Coriolis flowmeter. It should be noted that the amplitude of the error will be different following the size, but it was systematic under reading that was established with this manufacturer's product.

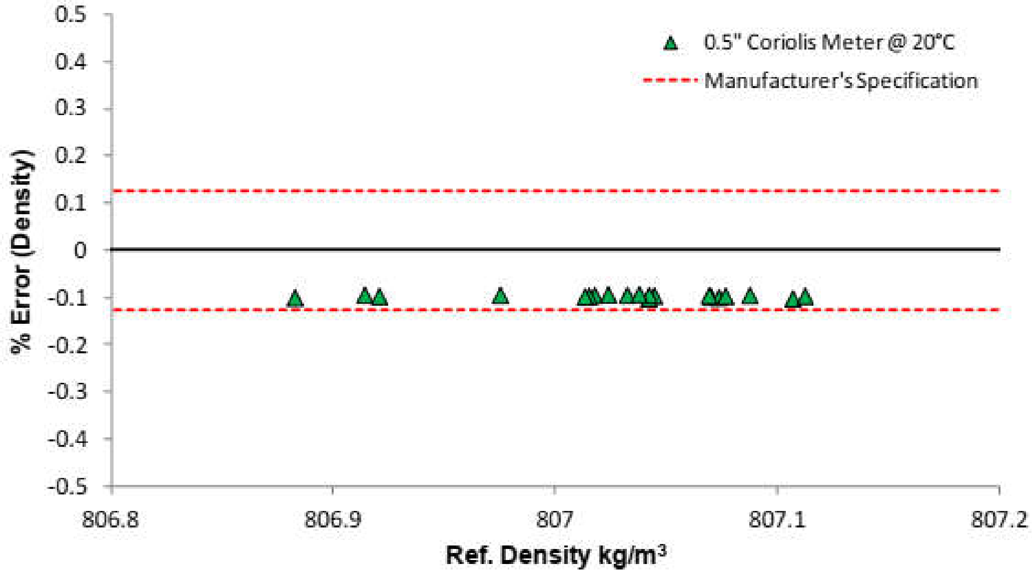


Figure 4: Uncertainty on the Coriolis density used in the oil line and calibrated by the Coriolis manufacturer in water (standard procedure)

It should be noted that manufacturers of Coriolis flowmeters are providing a specification with a single-phase. There are no performance specifications supplied for two-component mixtures of liquid. Therefore, this statement shows the importance of evaluating the performance of the Coriolis flowmeters in such conditions and obviously to establish the associated uncertainty. Figure 5 here below is showing the uncertainty of different Coriolis flowmeters from 1.5-inch and 3-inch for a range of flowrates and also versus water cut variation. Overall, it can be stated that such Coriolis is performing well within ±1% uncertainty on the mass flowrate. Interestingly, it could be noted that better performance was outlined in water with oil contamination than in oil with water contamination (Figure 6). This means that even if two identical Coriolis flowmeters are used in the oil and water lines and if the contamination is 5% in both Coriolis flowmeters respectively, either with oil and water, the uncertainty associated with the mass flowrate will be different, and therefore specific uncertainty calculations are required for each Coriolis flowmeter.

As expected, when the mass flowrate is becoming smaller than the uncertainty is increasing, but usually on the high-quality third-party facility, there are multiple reference measurement devices following the flowrates, and therefore an optimal sweet spot could be defined for each Coriolis. The maximum display error is at low water cut and low mass flowrate and could be established around ±1.1%.

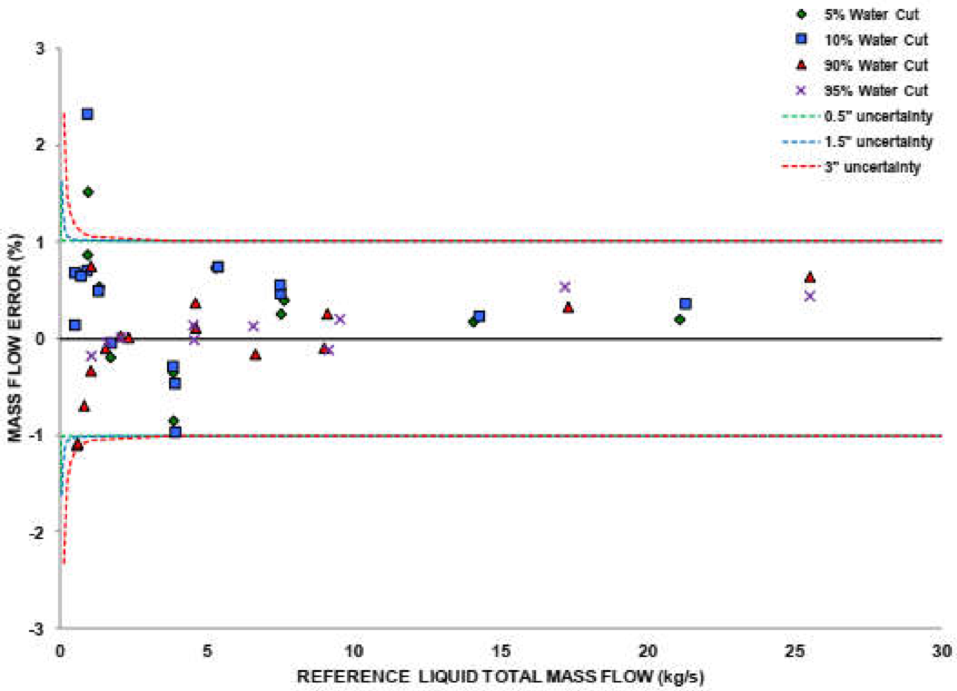


Figure 5: Uncertainty in Mass Flowrate for a Coriolis flowmeter calibrated at the Manufacturer facility initially.

The performance with mass flowrate being quite successful, this subsection is focusing on the density performance. Again, it should be noted that there are no claims provided regarding the quality of the density measurement when two-phases are flowing through a Coriolis flowmeter. The specifications given by the manufacturer relate only to single-phase applications. Similar to the mass flowrate performance presented above, the density performance is strongly dependent on the liquid velocity and the level of contamination of the secondary component inside the primary phase. It should not be surprising to see that the performance of the mixture density has a lower scattering or better uncertainty, while the density of the mixture is close to the water density phase. Again, this is related to the fact that the water is used for establishing the factor of the Coriolis calibrations.

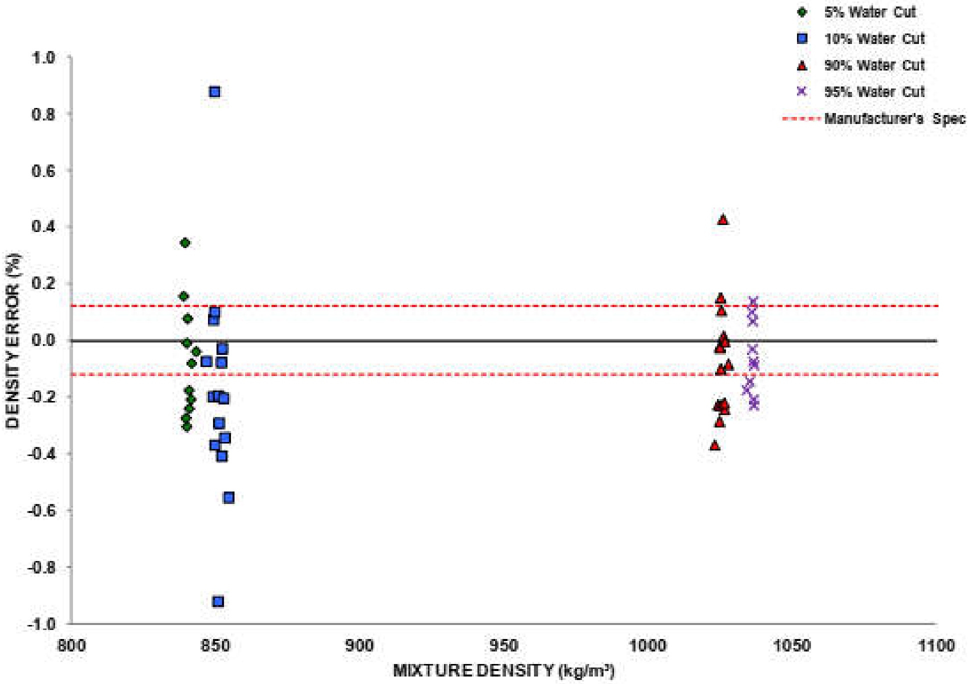


Figure 6: Density Deviation of the Coriolis versus Density and Water cut (i.e., contamination of the single-phase)

Note: Accuracy of the density measurement is well within ±0.9%. If such Coriolis were used to monitor the level of contamination, using this additional uncertainty will lead to an error on the water cut of 3.5% (Reference [1]). It is then essential that excellent density performance is achieved to calculate the water cut accurately and calculate the cross-contamination correctly. It is, therefore, essential that the performance evaluation is carried out in the same conditions as expected during the use at the facilities to establish the correct uncertainty claims associated with such challenging conditions. The result of this test program has shown clearly that an additional error due to the secondary component contamination should be accounted for as a source of uncertainty on the mass flowrate measurement and density measurement in these specific conditions. As said earlier, it is essential to note that Coriolis manufacturers' uncertainty claims correspond to calibrating equipment in single-phase water and low pressure only, and this extra uncertainty is due to the non-compliance by the user (third party facility) with the expected conditions anticipated.

We're proposing below an analytical method for uncertainty analyses that should be adopted in line with the GUM concept and presented as step-by-step process:

1. Define the relationship between all the inputs to the measurement and the final output
2. For each of input, establish the list of all the factors that contribute to the uncertainty for that input
3. Estimate the magnitude of the uncertainty for each factor
4. Establish a standard uncertainty for each source
5. Estimate the effect of each input parameter on the output result; this will be achieved by calculating the sensitivity coefficients.

6. Combine all the input uncertainties using the table concept presented earlier to obtain the overall uncertainty for the final parameters.
7. Express the overall expanded uncertainty by applying the relevant K factor following the distribution type.

Under such possible contamination condition, the common sources of uncertainty for the reference flowmeters should be rewritten with a fifth additional uncertainty as presented below:

1. Calibration uncertainty
2. Equation fit uncertainty
3. The drift uncertainty
4. Uncertainty about the mean
5. **Two-component effect**

Earlier, the explanation about the calibration uncertainty, the equation fit uncertainty, the drift uncertainty, the uncertainty about the mean has been introduced. The last one is the two-component effect, which refers to the contamination of one phase by another fluid, and it must be considered inside the uncertainty budget. It will be demonstrated that performance evaluation tests should be carried out in order to establish such error likely to occur under some operating conditions at the third party facility, especially if the design of the separator was either too small or oil and water flowrates are too high or in proportion which leads in all cases to a retention time too short for complete separation of the oil and water phases.

6.2.3. Factual statements about the Coriolis flowmeter performance in general

This section is planning to establish the correct statement about the uncertainty of the Coriolis flowmeter used as a reference flowmeter if the Coriolis selected has been going through some specific test to establish the performance versus line pressure, and Reynolds number (or versus the viscosity). As a reminder, Coriolis flowmeters have a dependency versus pressure and temperature, and this can be easily explained by referring to Young's modulus, as the pressure and temperature are increasing or decreasing the stiffness of the material used for the tube inside the Coriolis, and therefore this will have an impact on the vibration of the tubes and will lead to a deviation in terms of measurement of density and mass flowrates. Here below in figure 7, is presented, as an example, the deviation against reference at different pressures for the same Coriolis flowmeter. The correction coefficient to be applied versus pressure is usually a value in the range of 0.009%/bar. This could be seen as a very small value, but let's take 20 bar as line pressure, leading to a correction to be applied of 0.18%, which is significant and roughly twice the uncertainty claims on the Coriolis flowmeter itself. This correction factor is significant and becomes critical for allocation measurement with direct impact on revenue or sharing. This is also why NEL has a dedicated facility capable of calibrating Coriolis flowmeters at high pressure (100 bar) and high temperature (80°C) to establish, with reasonable accuracy, the actual correction coefficient to be applied. This correction coefficient cannot be generic because it depends on a lot of mechanical parameters, and it is size-dependent. One example was given in the paper reference [4] about the importance of this correction factor, where Coriolis were tested from 4 to 60 bar, and the uncertainty value on mass flowrate has been changed from initially 0% to close to 0.5%.

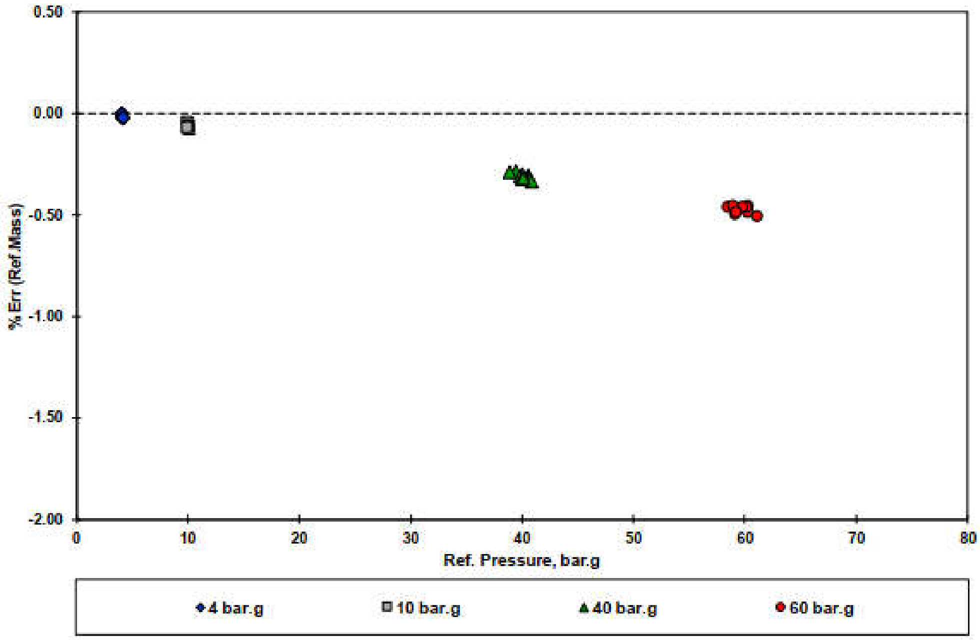


Figure 7: Typical Response of Coriolis versus Line Pressure

In the same paper, the dependency versus Reynolds number is also presented and showing that the viscosity effect can lead to the uncertainty on the readings beyond the ±0.1% expected.

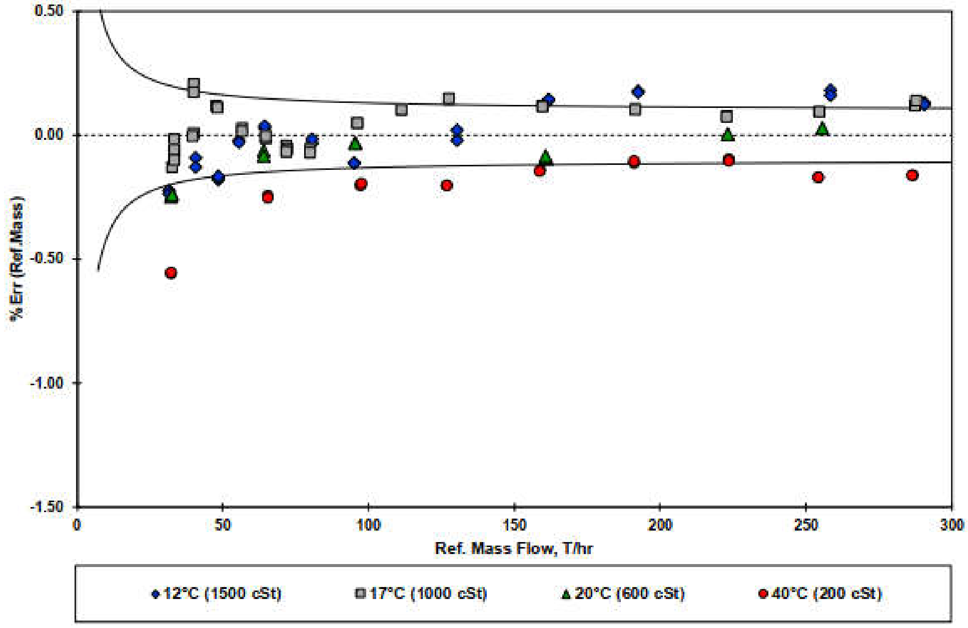
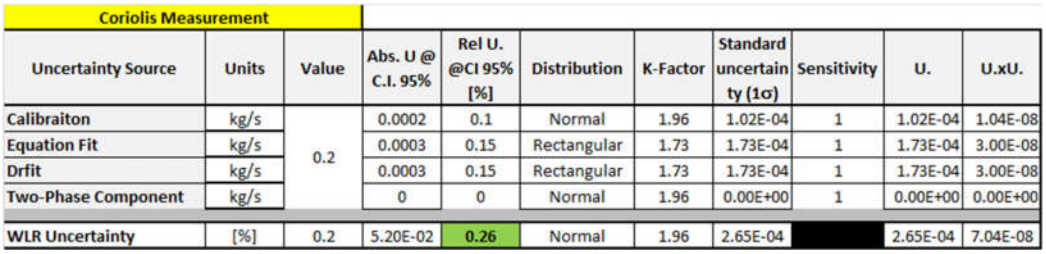


Figure 8: Deviation of the flowrate measured by Coriolis versus flowrates and viscosities.

The viscosity range presented in figure 8 is quite high, but two things should be highlighted; first, at low viscosity, there is a systematic under reading when at high viscosity, there is over reading. Secondly, this type of viscosity could be encountered with oil and water emulsions.

Let’s assume that the pressure and viscosity dependency have appropriately been corrected; the overall uncertainty for the Coriolis flowmeter could be established as presented in table 9 here below:



Coriolis Measurement

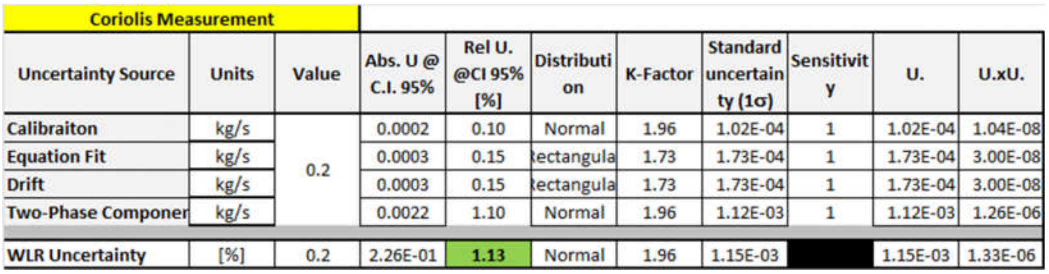
Uncertainty Source	Units	Value	Abs. U @ C.I. 95%	Rel U. @CI 95% [%]	Distribution	K-Factor	Standard uncertainty (1σ)	Sensitivity	U.	U.xU.
Calibraiton	kg/s	0.2	0.0002	0.1	Normal	1.96	1.02E-04	1	1.02E-04	1.04E-08
Equation Fit	kg/s		0.0003	0.15	Rectangular	1.73	1.73E-04	1	1.73E-04	3.00E-08
Drfit	kg/s		0.0003	0.15	Rectangular	1.73	1.73E-04	1	1.73E-04	3.00E-08
Two-Phase Component	kg/s		0	0	Normal	1.96	0.00E+00	1	0.00E+00	0.00E+00
WLR Uncertainty	[%]	0.2	5.20E-02	0.26	Normal	1.96	2.65E-04		2.65E-04	7.04E-08

Table 9: Uncertainty Budget for Coriolis Measurement in single-phase flow

The uncertainty from the manufacturer stating ±0.1% when considering the drift and fitting equation uncertainties leads to an overall uncertainty 2.5 times the manufacturers' claims. To reduce this uncertainty, it is necessary to have longer historical calibration records of this specific Coriolis flowmeter. This can be done over time or with a higher frequency of calibration. This will compensate for the drift. The fit equation will require more data to be collected at multiple conditions and probably a higher polynomial fit.

6.2.4. Uncertainty of the Coriolis flowmeter in Two-Phase Conditions

In the previous section, it was established that the maximum error for the presented Coriolis flowmeter was observed at low water cut and low flowrate with a deviation value of ±1.1%. It should be highlighted that this value expresses the uncertainty of the Coriolis flowmeter on the full range. We could imagine that a specific range of uncertainty is given at a low flowrate and a different one is provided at higher flowrate. Taking the split versus the mass flowrate at around 5 kg/s it is possible to claim an uncertainty respectively for the lower mass flowrate ±1.1% and higher mass flowrate around ±0.30%. It is now possible to calculate the overall uncertainty taking into account the two-phase component as presented in table 9 here below for the low mass flowrate:

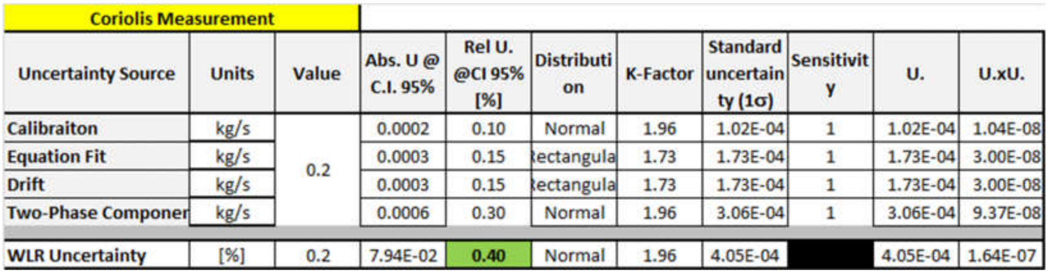


Coriolis Measurement

Uncertainty Source	Units	Value	Abs. U @ C.I. 95%	Rel U. @CI 95% [%]	Distribution	K-Factor	Standard uncertainty (1σ)	Sensitivity	U.	U.xU.
Calibraiton	kg/s	0.2	0.0002	0.10	Normal	1.96	1.02E-04	1	1.02E-04	1.04E-08
Equation Fit	kg/s		0.0003	0.15	Rectangular	1.73	1.73E-04	1	1.73E-04	3.00E-08
Drift	kg/s		0.0003	0.15	Rectangular	1.73	1.73E-04	1	1.73E-04	3.00E-08
Two-Phase Component	kg/s		0.0022	1.10	Normal	1.96	1.12E-03	1	1.12E-03	1.26E-06
WLR Uncertainty	[%]	0.2	2.26E-01	1.13	Normal	1.96	1.15E-03		1.15E-03	1.33E-06

Table 10: Uncertainty Budget for a Coriolis Measurement in two-component flow with low mass flowrate

For the high mass flowrate, the uncertainty budget can be established as presented hereafter (table 11):



Coriolis Measurement

Uncertainty Source	Units	Value	Abs. U @ C.I. 95%	Rel U. @CI 95% [%]	Distribution	K-Factor	Standard uncertainty (1σ)	Sensitivity	U.	U.xU.
Calibraiton	kg/s	0.2	0.0002	0.10	Normal	1.96	1.02E-04	1	1.02E-04	1.04E-08
Equation Fit	kg/s		0.0003	0.15	Rectangula	1.73	1.73E-04	1	1.73E-04	3.00E-08
Drift	kg/s		0.0003	0.15	Rectangula	1.73	1.73E-04	1	1.73E-04	3.00E-08
Two-Phase Componer	kg/s		0.0006	0.30	Normal	1.96	3.06E-04	1	3.06E-04	9.37E-08
WLR Uncertainty	[%]	0.2	7.94E-02	0.40	Normal	1.96	4.05E-04		4.05E-04	1.64E-07

Table 11: Uncertainty Budget for a Coriolis Measurement in two-component flow with high mass flowrate

These analyses show that there is a significant increase in the overall uncertainty because of the second phase contaminant within a given expected single phase. This exercise shows that cross-contamination has by far the most significant effect on the overall uncertainty, and all operators on the third-party facilities should always ensure that the separation is perfect or a retention time inside the separator is long enough. The consequence could be that the facility may not be able to handle all flowrates from 0 to 100% WLR with a low uncertainty claim. It is also highlighting that a continuous measurement of the cross-contamination is the only way to achieve a low overall measurement uncertainty adequately.

6.2.5. Recommendations and Best Practice for Coriolis flowmeters

NEL had multiple research and development programs related to the performance of the Coriolis flowmeters. The following recommendations came as the best practice:

1. The mass flowrate and density in two-component (liquid) performance is dependent on the mixture homogeneity. It was found that a minimum distance of 5D of the Coriolis after a bend is recommended.

2. Coriolis manufacturers do not supply specifications of the performance in two-phase or two-component mixtures. Therefore, a specific program should be formulated to determine the performance in terms of mass flowrate and density

3. It was found that the performance of Coriolis was way better when the velocity of the liquid is above 1 m/s.

4. The claim about the uncertainty on the Coriolis flowmeter versus pressure and viscosity should be carefully evaluated. It was found that significant errors could be obtained when the pressure is increasing, or the viscosity is becoming more significant.

5. The analyses presented inside this document is referring only to the contamination of a liquid phase by another liquid phase; it should be kept in mind that the presence of gas inside the liquid single-phase will have a drastic effect the overall uncertainty. Overall deviation beyond 5%, even with little contamination, could be obtained. This demonstrates that the

importance again of the quality of the gas-liquid separation or a two-stage separator shall be firmly recommended to ensure that there is no carry-under or designing a system with pre-separation or conditioning of the flow before entering the separator to ease this gas-liquid split as quickly as possible.

6. Overall, the performance of the Coriolis flowmeter is always better at higher flowrate; this could be related to the fact that adequate mixing of the components is occurring at higher velocities.

7. The experience acquired with one brand of Coriolis flowmeter cannot be translated, in terms of value, to another brand; systematically studies should be carried out in case of different sizes, and options selected for the reference Coriolis or brand.

8. The two-component liquid effect is by far the most significant contributor to the overall uncertainty for the mass flowrate and the density.

9. It should always be kept in mind that flowmeter manufacturers' uncertainty claims correspond to calibration in a single phase of water or oil. There is a significant increase in the uncertainty to consider the two-phase component of the mixture.

10. The order of magnitude of the uncertainty on the reading from a Coriolis flowmeter is way more significant if there is a presence of gas, even at very low value of gas volume fraction (GVF) within 0 to 5% (reference [1]).

7. CALCULATION OF THE REFERENCE MEASUREMENT AT DEVICE UNDER TEST (DUT) CONDITIONS

Now that the explanation of establishing the reference measurement and the associated uncertainty for each key parameter at reference conditions has been made, in this chapter will be shown how to convert these measurement values at DUT conditions. Before proceeding immediately on the flowrates correction, we need to evaluate the uncertainty associated with the pressure and temperature transmitter, which follows the same approach as presented before, which means calibration uncertainty, equation fit uncertainty, drift, and the mean uncertainty is accounted for, as a minimum.

7.1. Representativeness of the Mixture Temperature in Multiphase or Wet Gas Facilities

Up to this stage, there was little doubt about the representativeness of the temperature measurement; now we are dealing with a multiphase flow which could have different flow structure from stratified, annular, plug, slug, and even a bubble flow. The first question is: do we measure the temperature correctly of the mixture? Indeed, in most of the facilities, the gas phase is not conditioned, and the temperature of the gas may be lower at the mixing point than the temperature of the liquid. We are usually doing only a few single reference temperature measurements around the DUT, and we assume that this is representative of the phase mixture temperature. If there is any doubt about this measurement, a test program should be carried out and documented to validate if this assumption is fair and justified.

NEL has been applying such a concept and elaborates on a gas-liquid mixture temperature program with a recording made at different points in terms of distance from the mixing point from 0 to more than 65m away. From the study, it was concluded that after around 10m from the gas-liquid mixing point across the full range of multiphase flow patterns and velocities, the temperature of the gas-liquid mixture was homogeneous. As the main conclusion, the MPFM or WGFM under test should be located at least 10m away from the mixing point, and the temperature measurement will be representative of the multiphase mixture temperature.

With inert fluid, the pressure representativeness in the multiphase or wet gas facilities has little doubt as soon as (like all the other component of measurement) it has been calibrated at least in the last 12 months (maximum duration), and the pressure point set for the reading is complying with the relevant standards. Another step to consider is to be sure that there is no liquid coming inside the tubing or the tubing is always filled with a selected fluid which has been considered during the calibration. As indicated earlier, the atmospheric pressure should be able to provide, especially at low pressure, the absolute pressure with the best uncertainty.

7.2. Philosophy to Address the Measurement at DUT

At this stage, the evaluation of the uncertainty of the reference measurement to be converted to the DUT flow conditions should have been established for all the parameters at the respective reference single-phase flowmeter, but also the proper reading of the temperature and pressure upstream and downstream of the DUT and at DUT conditions. The calculation of the respective flowrates at DUT will be obviously more cumbersome when using a live fluid because there will be some mass transfer between the phases at the different line pressures. Failing to address the uncertainty of the mass transfer correctly will lead to errors in the assessment of the performance of the multiphase or wet gas flowmeters, which could be over-optimistic or pessimistic following the cases. As indicated previously, the mass transfer of gas dissolved in oil or/and water may become free gas at the device under test and will be read as such by the DUT. Using correct Equation of State (EOS) describing the phenomena to be modeled with the according assumption based on strong statements or experiments that some value about the quantity of gas transferred to free gas will be generated and then "creating" this free gas.

A specific section (7.7 Practical Case) will be addressing this problem of solubility of each phase against the others. The equations to establish the volumetric flowrate of each phase is at different line pressure and temperature are well established and will be highlighted and can be established with around 10 parameters (based on PVT knowledge from literature or equation of state (EOS) calculation) that needs to be considered for the relevant evaluation of the flowrates at the DUT. The list of 10 parameters to take into account in a full PVT development and described in detail later but quickly listed here as: density of each phase (3 parameters), Volume Factor for each phase (3), Dissolution of gas in oil and water phase at line conditions (2), Dissolution of liquid (water and oil) in gas phase at line conditions (2).

Another point that is essential to understand is: what output parameters of the DUT will be compared to the reference measurement? Perhaps volumetric flowrates or mass flowrates? Is it a comparison at line conditions, and usually at DUT conditions, or is it a comparison at standard conditions? Following the type of comparison, the impact of the PVT model will be significant. It shouldn't be anticipated that the DUT condition is close to the reference measurement, and the correction factor to apply is small or close to 1. The propagation of error may not be limited to only the uncertainty at reference conditions. The comparison needs to be done at the condition following the variation of pressure and temperature from the reference measurement to DUT condition, and the propagation of error will be impacting the overall uncertainty of the reference measurement significantly.

For any reference flow measurement device used, even Coriolis flowmeter providing measurement at the given line pressure and temperature conditions, there is no way of knowing how the flow will evolve after flowing through the single-phase reference flowmeters. This can be understood by the fact that the process followed by the fluid from line to standard conditions is unknown.

Note: The same process applied with the use of a separator, and if some users or readers may believe this is not happening, a careful check in the data processing and associated calculation of the flowrates at standard conditions will show that (for example, the use of shrinkage factor).

7.3. Total Mass Flowrate Measurement: A specific case

Irrespective of the type of fluids present inside the facility (transfer of mass between the phases or not), the only measurement which is constant whatever the pressure and the temperature conditions are the total mass flowrates. This should be the parameter to use to study the philosophy used for the calculation to establish the proper conversion of the volumetric flowrates from reference measurement to DUT conditions, or to verify that the conversion is correct. Any deviation on the comparison of the recalculated mass flowrate at DUT versus reference should give already a statement about the best claim possible on the overall uncertainty. The difference if existing is due to the calculation and assumption in the model for calculation; indeed, ideally, the two total mass flowrates should be identical.

7.3.1. with Inert fluids and comparison at line conditions

As a caution, this section is developed to look at purely the performance at the DUT. Inert fluid refers to fluids that are either a stabilized crude oil, kerosene, nitrogen, etc, and they are not “contaminable” to each other. The significant interest of this type of fluid is if an injection of gas and liquid is done at a reference point, then the same mixture of fluid will be passing through the flowmeter. There is no exchange of molecules between the phases; the mass of each phase remains constant, and the volume, if corrected for the Pressure and Temperature, is the same (same number of molecules for oil, water, and gas in each associated phase).

With inert fluids, it is easier to look at the DUT performance. The setting of the MPFM or WGFM should be easier knowing that most of the time, the gas phase is Nitrogen. It is also the same process for the oil, which is often a type of Kerosene with a dedicated setting. Some facilities might use crude oil or propose such an option against kerosene and could be an option, especially if the MPFM technology requires a more homogenous flow, and there are no mixing devices capable of providing such mix.

The use of inert fluids will allow the MPFM and the flowloop to have the same behavior for density of oil, water, and gas versus pressure and temperature. A very high level of accuracy can be achieved and demonstrating the actual signature/performance of the DUT. This is the perfect combination of fluids to establish the performance of new technology. The measurement uncertainty associated with mass transfer between the phases is eliminated from the analyses and then reduces the propagation of error.

7.3.2. with Inert fluids and comparison at standard conditions

The interest in this type of comparison is to decouple the overall uncertainty between the metrology performance of the DUT (as mentioned in the previous chapter) and the one associated with the PVT package (conversions from DUT and reference conditions to standard conditions). The conversion of the flowrates of the different phases at reference flowmeters will be made by considering a full PVT development. This solution is ideal for establishing and distinguishing the main errors between the flowmeter performance and the PVT Package embedded inside the MPFM or WGFM; this will ensure a proper audit of the two steps. The limitation could be that some of the parameters of the PVT package are not used or set to 0, and then this is not giving a full picture of the final performance in field conditions. This point will be reviewed later.

7.3.3. with Live fluids and comparison at standard conditions

With live fluid, there is an exchange of molecules between the different phases, and this needs to be considered in the reference calculations. This means that even if the fluid has been stabilized to a specific temperature and pressure (usually running them for a while to achieve a proper mixture and dissolution -think about gas inside a sprite-like a Soda maker-), then when the reference flowmeter will indicate a given value; at the DUT conditions usually lower P (and maybe temperature) then some of the gas dissolved inside the oil is coming out of solution. There is no longer a constant mass of oil from reference flowmeter conditions to MPFM and WGFM conditions because some of the gas molecules dissolved inside the oil are coming out of solution, but also the mass of gas and the composition is also different with these molecules coming out from solution. This mass transfer or molecule exchanges need to be considered on such flowloop facilities to achieve reasonable accuracy.

Additionally, what needs to be understood is that the quantity of gas coming out of solution is depending on the difference of pressure between the reference flowmeter and the MPFM or WGFM. This is not a simple constant versus pressure. It is then necessary for the flowloop facility using live fluids to know the pressure and temperature at flowmeter conditions to be able to do the correction of the reference measurement and take care of the dissolution or mass transfer. It is also important to have an accurate model about the dissolution of one phase in the other.

The correction is necessary, especially with the level of specifications of some MPFM, and WGFM manufacturers are claiming nowadays being within few percent uncertainties. The reference measurement is not anymore coming from a reference (i.e., directly from a calibrated flowmeter alone), but a combination of a reference flowmeter and an Equation of State (EOS) or Dedicated PVT package for this given facility and the overall uncertainty of the reference measurement will take both uncertainties into account.

Such facilities will have obviously more substantial uncertainty for the same quality of work than one with inert fluid, but it could be said that the situation is more representative of the field conditions. Unfortunately, the live fluid is not representing the entire capability or conditions met in the field conditions. An additional study of the PVT Package should be completed and demonstrated to be accurate based on some laboratory verification that should be documented to establish the associated uncertainty.

As seen in such a case there is little differentiation between a live fluid and inert fluid because the correction is done by the facility flowloop operators and not by the manufacturer of the MPFM, which is solely reporting the flowrate performance of its equipment for a direct comparison. The interest will be to bring the performance to standard conditions, but the DUT should be fed with the same PVT package used by the facility. Indeed, the GOR total is not constant on the facility, the test matrix is not based around this parameter but versus GVF, and then this means that each data point recorded for a set of oil, water, and gas flowrate is representing a different well and different reservoir conditions. This was the aim of this test, but in any case this is used to verify the PVT package performance.

The relative complexity of the use of live fluids could be balanced by the fact that some MPFM or WGFM may provide better performance with live gas than inert gas (signature being different with nitrogen versus a combination of C1 to C4), but on the other side the gas composition should be checked regularly. The crude oil, usually a dead oil, may also be more attractive for some technology assuming a certain quality of mixing.

7.3.4. with Live fluids and comparison at standard conditions

As indicated above the relative complexity of the use of live fluids could be balanced by the fact that some flowmeters may provide better performance due to improved mixing process. The idea to check the performance at standard conditions versus line conditions will, in this case, use the PVT Package, which is an option usually embedded inside the MPFM flow computer, and it could, in some cases, show the weakness or not of this implementation. It should be noted that this could be addressed by a desk study.

For the use in such conditions, it is essential to have a proper understanding of the transfer of mass between the phases, and it should be clear that this effect, even if it is a limited one, should be considered for high accuracy. It should be clear that usually it is either based on the dissolution of the gas inside the oil or the condensation of some of the gas at standard conditions.

Note: There is no flowloop capable of taking all effects as encountered in the field conditions, and a desk analysis could be necessary to complete the entire study.

The data flow processing will be in this case following this path in a generic way:

1) the reference measurement from the reference single-phase facility will be converted to standard conditions considering the gas dissolved, for example, at higher pressure.

2) The model of PVT or EOS used for this flowloop facility will be downloaded to the MPFM before the test and fit around the range of Pressure and Temperature expected to be met.

3) The flowmeter being loaded with the PVT information; when the fluid flowrate will be measured (i.e., at line conditions), then the conversion will be done automatically to standard conditions.

4) It is then possible to make the comparison with the reference measurement converted at standard conditions. It is understood that it is essential in such cases to have the same PVT package unless this will provide a deviation in the comparison not due to the flowmeter metrology but the conversion package.

As said earlier, in practice, there is no flowloop capable of reproducing the entire field conditions, but they can mimic the conditions of GVF, WLR, Viscosity, and in some cases, pressure and/or temperature. The flow metering community also understands that an MPFM or WGFM unable to pass such tests in a controlled environment has little chance of performing better in the field conditions. This verification should be considered necessary, especially if there is tax associated with such reading or gain or loss of production to be stated between partner or custody transfer application, or government tax or regulation applying.

7.3.5. Schematic of the phase transfer from P1, T1 conditions to P2, T2 Conditions

The calculation of the densities and flowrates at the DUT could be done either by using the concept of mass or volumetric flowrate. This paper will be using the conversion based on volumetric flowrate from a given condition to another one; this is representing the traditional way of calculation and then using a concept well understood by the oil and gas industry.

Before introducing the equation and the concepts, we are presenting on figure 9 here below the evolution of the three phases (oil, water, and gas) from reference conditions on the left side to the device under test (DUT) and the warning associated with the calculation of either the flowrate or the densities which are different phases at DUT (different gas due to different composition and then density too). In this example, which is very generic, the fact that some gas was dissolved in oil but also in the water was considered; and there is potentially some oil and gas present inside the gas phase. The facilities are under pressure; therefore, some fluids can be dissolved in the other ones; the gas phase will at separator conditions become liquid (a type of gas condensate) at a lower pressure and temperature. We are representing this concept (figure 9) for the gas with some greenish and bluish colors to identify the oil and water dissolved inside the gas phase, the same convention on the color is used to represent what is dissolved inside the main phase of oil and water. The set of pie in the middle (figure 9) shows the difference in terms of volume between the calculation at reference conditions on the left side. The set of pie on the right side is to show what mathematically it will be necessary to do to calculate to the DUT conditions the quantity of gas, oil, water, and considering the different densities of each phase. Flowing through the gas reference measurement, if there is some condensate present, this one is in the form of gas, and therefore we have a single phase flowing through this reference flowmeter but not anymore at DUT conditions.

The first thing to do before testing any flowmeters, and that the fluids are from the atomic point of view stable is to flow for a given period to provide some exchange between the phases and get the relevant dissolution in each of them. The specific gravity of gas needs to be measured; this is always the best method than trying to estimate it, which will add more uncertainty. It means that the gas density or composition should be obtained in real-time versus the line pressure and temperature.

It should be noted that the gas phase is always evolving, for example, small leaks or, as seen by the authors, injection of "fresh natural gas", then the calculation and the estimation made by an equation of state will be incorrect.

The same type of consideration should be taken for the oil and the water if gas is dissolved inside the phases. As highlighted above, one of the best metering solutions available today will be the Coriolis flowmeter, which needs to be appropriately calibrated over the range of densities, which could be expected.

To generate a flow, the minimum requirement is a change of the line pressure between the two points, in this case represented by the reference flowmeter and the DUT. The change of the line pressure will allow some of the gas dissolved inside the oil and water come out and become free gas phase, which is Q1 and Q2 in figure 9 below. At the DUT, there is now three types of gas, the one coming from the gas line (free gas), the one coming out of the oil line which will have its composition and therefore specific gravity, and the one coming out of the water with also specific gravity and composition. For example, for the water phase, primarily the two-components that can dissolve easily inside the water are CO2 or H2S. The challenge, therefore, is to calculate the fraction of the three phases versus pressure and temperature (mass transfer) to be able to calculate the gas density at the DUT. In order to establish it, a dedicated equation of state (EOS) should be developed based on the full composition of the three phases: oil, water, and gas, with their level of gas dissolution inside each of them. Then recombination should be made mathematically based on the ratio of each phase for a given flow condition. To be able do it correctly, some measurements in laboratory about the dissolution of the phases in the other ones need to be established; the larger the number of points available, the better will be the curve fitting that will be used to establish the equation of states. As a reminder, we have demonstrated earlier that the fitting exercise is usually producing significant uncertainty in the overall uncertainty of reference flowmeter devices; this is precisely the same phenomena that will happen in such system with the EOS with the highly non-linear behavior.

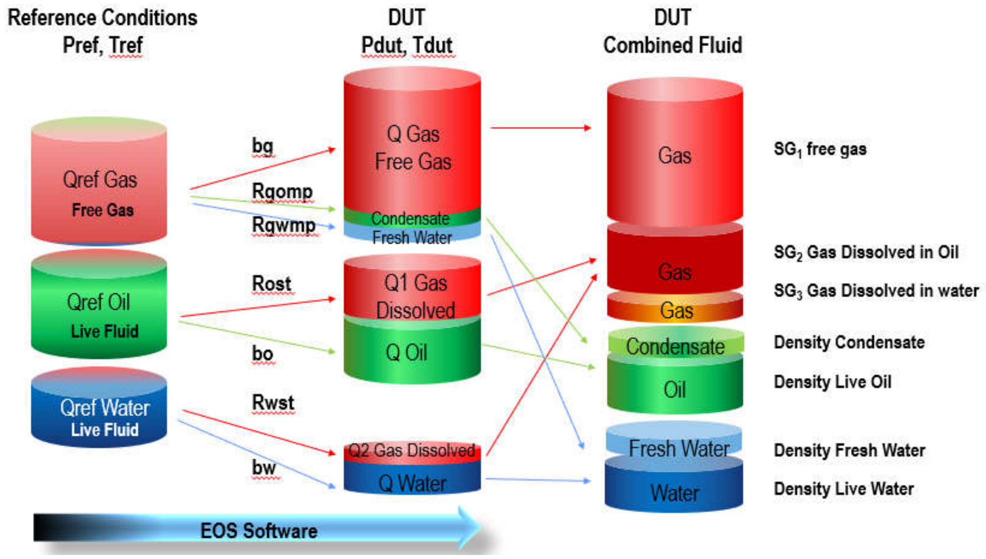


Figure 9: Typical mass transfer from each phase to another one when line and pressure conditions are changing

Note: it is essential to keep in mind that EOS will need to be pursued for each configuration of gas, oil, and water flowrates. There is not one equation of state that we could expect from the reservoir in the field conditions. Here the flow is changed by the pumping process which will affect the quantity of gas dissolved inside oil and water. In simple words, the GOR is not kept constant, but it is the same for the CGR and any of the parameters. Therefore, establishing the flowrates at DUT conditions will require some care and numerous laboratory tests for validation, and that should be documented and available.

The list of the parameters that should be an outcome of the Equations of state:

1) Gas in the oil phase ratio
2) Gas in water phase ratio
3) Water in gas phase ratio
4) Oil in gas phase ratio
5) Gas expansion factor
6) Oil shrinkage factor
7) Water shrinkage factor

These parameters are used for the calculation of the volumetric flowrate described in the next section. To establish the density of the mixture, some additional parameters are required as follows:

1) Density of the single-phase oil at DUT conditions
2) Density of the condensate or oil coming out from the gas phase at DUT conditions
3) Density of the single-phase water at DUT conditions
4) Density of the water (steam) coming out of the gas phase at DUT condition
5) Density of the free gas at DUT condition
6) Density of the gas coming out of the oil phase at DUT condition
7) Density of the gas coming out of the water phase at DUT conditions

7.4. Flowrates Evaluation at Flowmeter Conditions

Based on the definition given here above, it is possible to establish the oil, water, gas-phase at DUT conditions as presented here below with this set of equations:

$$Q_{VO@DUT} = Q_{VO@REF}.b_{O\_REFtoDUT} + Q_{VG@REF}.b_{g\_REFtoDUT}.R_{GO2\_REFtoDUT} \quad (11)$$

$$Q_{VW@DUT} = Q_{VW@REF}.b_{W\_REFtoDUT} + Q_{VG@REF}.b_{g\_REFtoDUT}.R_{GW2\_REFtoDUT} \quad (12)$$

$$\begin{aligned} Q_{VG@DUT} &= Q_{VG@REF}.b_{G\_REFtoDUT} + Q_{VO@REF}.b_{O\_REFtoDUT}.R_{OG2\_REFtoDUT} \\ &\quad + Q_{VW@REF}.b_{W\_REFtoDUT}.R_{WG2\_REFtoDUT} \end{aligned} \quad (13)$$

With the variable R_{xy2_AtoB} representing the mass transfer from the phase X to a phase Y, R_{GO2_AtoB} representing the gas becoming oil by changing from A to B conditions, R_{GO1_AtoB} representing the gas-oil ratio of the free phase from A to B conditions and b_{x_AtoB} representing the volume factor change from the conditions A to B. This can be an expansion factor for the gas or a shrinkage factor for the liquid and $b_{z\_AtoB} = {}^{V_{z\_B}}/_{V_{z\_A}} = {}^{V_{z\_B}}/_{V_{z\_SC}} . {}^{V_{z\_SC}}/_{V_{z\_A}} = {}^{b_{z\_AtoSC}}/_{b_{z\_BtoSC}} = {}^{b_{z@A}}/_{b_{z@B}}$ with SC representing standard conditions.

Only the propagation of error from the first equation will be presented hereafter, and it will be highlighted the sensitivity factor as introduced earlier inside table 12:

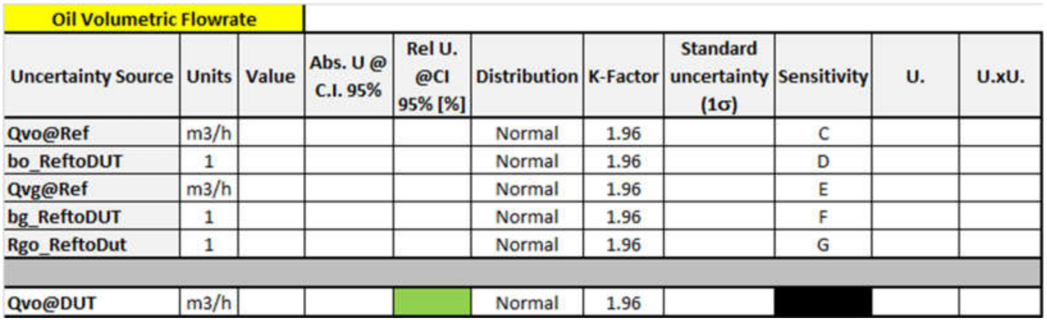
$$\frac{\Delta Q_{VO@DUT}}{Q_{VO@DUT}} = \sqrt{\begin{array}{l} \left(\frac{A}{Q_{VO@DUT}}\right)^2 \cdot \left(\left(\frac{\Delta Q_{VO@REF}}{Q_{VO@REF}}\right)^2 + \left(\frac{\Delta b_{O\_REFtoDUT}}{b_{O\_REFtoDUT}}\right)^2\right) \\ \quad + \left(\frac{B}{Q_{VO@DUT}}\right)^2 \cdot \left(\left(\frac{\Delta Q_{VG@REF}}{Q_{VG@REF}}\right)^2 + \left(\frac{\Delta b_{g\_REFtoDUT}}{b_{g\_REFtoDUT}}\right)^2 + \left(\frac{\Delta R_{GO2\_REFtoDUT}}{R_{GO2\_REFtoDUT}}\right)^2\right) \end{array}} \qquad (14)$$

with $A = b_{O\_REFtoDUT} . Q_{VO@REF} ; B = b_{g\_REFtoDUT} . Q_{VG@REF} . R_{GO2\_REFtoDUT}$ (15)

or

$$\begin{aligned} \frac{dQ_{VO@DUT}}{Q_{VO@DUT}} &= \frac{1}{Q_{VO@DUT}} \left[\begin{array}{r} b_{O\_REFtoDUT} . \delta Q_{VO@REF} + Q_{VO@REF} . \delta b_{O\_REFtoDUT} + b_{g\_REFtoDUT} . R_{GO2\_REFtoDUT} . \delta Q_{VG@REF} + \\ Q_{VG@REF} . R_{GO2\_REFtoDUT} . \delta b_{g\_REFtoDUT} + Q_{VG@REF} . b_{g\_REFtoDUT} . \delta R_{GO2\_REFtoDUT} \end{array} \right] \\ &= \frac{1}{Q_{VO@DUT}} \left[C . \delta Q_{VO@REF} + D . \delta b_{O\_REFtoDUT} + E . \delta Q_{VG@REF} + F . \delta b_{g\_REFtoDUT} + G . \delta R_{GO2\_REFtoDUT} \right] \end{aligned}$$

(16)

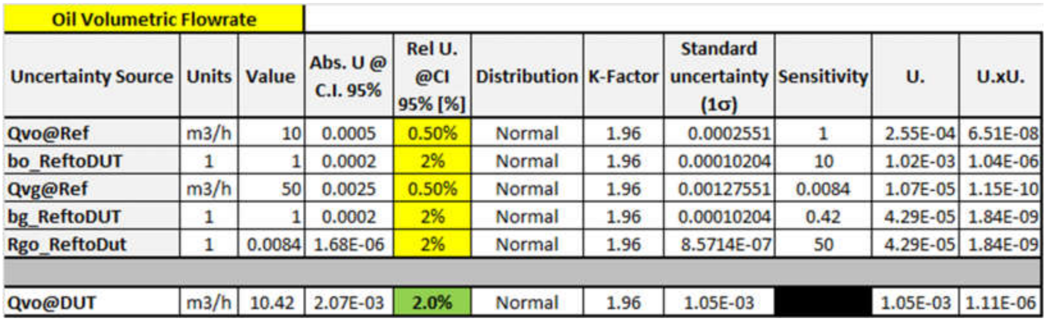


Oil Volumetric Flowrate

Uncertainty Source	Units	Value	Abs. U @ C.I. 95%	Rel U. @CI 95% [%]	Distribution	K-Factor	Standard uncertainty (1σ)	Sensitivity	U.	U.xU.
Qvo@Ref	m3/h				Normal	1.96		C		
bo_ReftoDUT	1				Normal	1.96		D		
Qvg@Ref	m3/h				Normal	1.96		E		
bg_ReftoDUT	1				Normal	1.96		F		
Rgo_ReftoDut	1				Normal	1.96		G		
Qvo@DUT	m3/h			🟩	Normal	1.96		■		

Table 12: Uncertainty Budget for an Oil Volumetric Flowrate at DUT conditions

A simulation was made assuming an uncertainty on the shrinkage factor of ±2% and the same value for the expansion factor and the gas dissolved inside the oil. It was assumed an uncertainty on gas and oil flowrate to be within ±0.50%, propagation of error leads to an uncertainty on the oil flowrate at the DUT conditions of ±2.0% (Table 12). This is roughly 4 times larger than the uncertainty at reference conditions.



Oil Volumetric Flowrate

Uncertainty Source	Units	Value	Abs. U @ C.I. 95%	Rel U. @CI 95% [%]	Distribution	K-Factor	Standard uncertainty (1σ)	Sensitivity	U.	U.xU.
Qvo@Ref	m3/h	10	0.0005	0.50%	Normal	1.96	0.0002551	1	2.55E-04	6.51E-08
bo_ReftoDUT	1	1	0.0002	2%	Normal	1.96	0.00010204	10	1.02E-03	1.04E-06
Qvg@Ref	m3/h	50	0.0025	0.50%	Normal	1.96	0.00127551	0.0084	1.07E-05	1.15E-10
bg_ReftoDUT	1	1	0.0002	2%	Normal	1.96	0.00010204	0.42	4.29E-05	1.84E-09
Rgo_ReftoDut	1	0.0084	1.68E-06	2%	Normal	1.96	8.5714E-07	50	4.29E-05	1.84E-09
Qvo@DUT	m3/h	10.42	2.07E-03	2.0%	Normal	1.96	1.05E-03	■	1.05E-03	1.11E-06

Table 13: Example of uncertainty Budget for an Oil Volumetric Flowrate using Coriolis flowmeter with live fluid

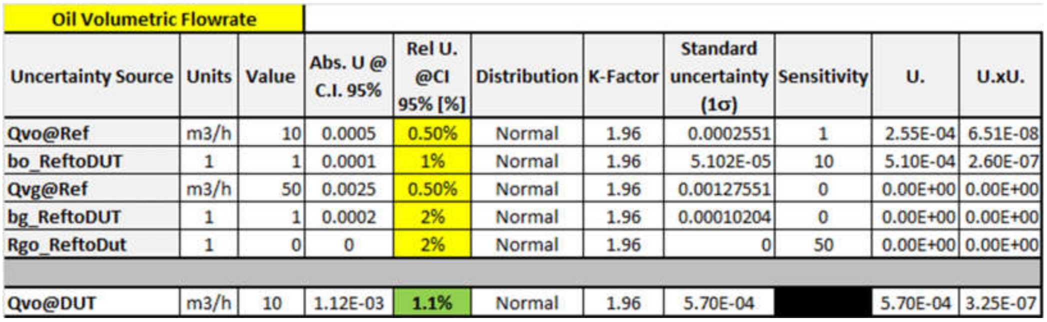
7.4.1. with Live fluids and Uncertainty Evaluation

Based on this example, the main factor affecting the oil volumetric flowrate is the estimation coming from the equation of state. To reduce such uncertainty, lots of measurements in laboratories of the gas dissolved in oil, and the shrinkage of the oil versus pressure and temperature should be taken. Another way will be to have the solution of gas inside the oil as small as possible; this will lead to a smaller variation of the shrinkage; in other words, the volatility of this oil should be as small as possible, which at the extreme means a dead oil/refined oil.

In such a situation as presented above, with the expectation that the uncertainty in flowrate measurement calculated from the reference at DUT conditions should be better (smaller) than the expected flowmeter performance under test. It is impossible to establish the performance of multiphase flowmeters flowrates specification claiming 6 to 8% (a ratio 3 to 4 times the third-party uncertainty).

7.4.2. with Inert fluids and Uncertainty Evaluation

The benefits of the inert fluid, sometimes referred to as immiscible fluid, is linked to the traceability on the shrinkage factors and the fact that the dissolution in the best case of the gas inside the oil is close to 0. To highlight this benefit, the previous case was rewritten with this time uncertainty on the shrinkage factor of ±1% against ±2% and no dissolution of the oil inside the gas. The benefit is an immediate improvement of the overall uncertainty by almost a factor 2.



Oil Volumetric Flowrate										
Uncertainty Source	Units	Value	Abs. U @ C.I. 95%	Rel U. @CI 95% [%]	Distribution	K-Factor	Standard uncertainty (1σ)	Sensitivity	U.	U.xU.
Qvo@Ref	m3/h	10	0.0005	0.50%	Normal	1.96	0.0002551	1	2.55E-04	6.51E-08
bo_ReftoDUT	1	1	0.0001	1%	Normal	1.96	5.102E-05	10	5.10E-04	2.60E-07
Qvg@Ref	m3/h	50	0.0025	0.50%	Normal	1.96	0.00127551	0	0.00E+00	0.00E+00
bg_ReftoDUT	1	1	0.0002	2%	Normal	1.96	0.00010204	0	0.00E+00	0.00E+00
Rgo_ReftoDut	1	0	0	2%	Normal	1.96	0	50	0.00E+00	0.00E+00
Qvo@DUT	m3/h	10	1.12E-03	1.1%	Normal	1.96	5.70E-04		5.70E-04	3.25E-07

Table 14: Example of uncertainty Budget for an Oil Volumetric Flowrate using Coriolis flowmeter with live fluid

Even for facilities using nitrogen, there is always a dissolution of gas inside the oil; this is seen when looking at typical gas composition analyses from the reservoir; there is always the presence of some nitrogen that was dissolved under the reservoir pressure and temperature. It cannot be said that the Nitrogen is inert. The interest using it with some refined oil is that the concentration is not pressure and temperature dependent. This has been extensively analyzed, and a large amount of data is available. For a line pressure above 5 bara, the concentration of the gas nitrogen inside the oil is roughly constant.

Said in other words, the translation of flowrate measurement from reference condition to DUT conditions is straightforward; however, the conversion from reference condition to standard conditions needs to consider this gas dissolution and, in this case it is comparable with live fluid. The essential difference is that the uncertainty of the dissolution is better than what can be expected from and equation of state.

7.5. Mass Flowrate Evaluation at Flowmeter Conditions

In this section, the approach to calculating the mass flowrate at DUT conditions based on the density values of the oil, water, and gas phases flowing through each single-phase reference flowmeter is presented in equations 17, 18 and 19 below.

$$\begin{aligned} Q_{mO@DUT} &= Q_{VO@REF}.b_{O\_REFtoDUT}\cdot\rho_{O@DUT} \\ &\quad + Q_{VG@REF}.b_{g\_REFtoDUT}.R_{GO2\_REFtoDUT}\cdot\rho_{GO\_REFtoDUT} \end{aligned} \tag{17}$$

$$\begin{aligned} Q_{mW@DUT} &= Q_{VW@REF}.b_{W\_REFtoDUT}\cdot\rho_{W@DUT} \\ &\quad + Q_{VG@REF}.b_{g\_REFtoDUT}.R_{GW2\_REFtoDUT}\cdot\rho_{GW\_REFtoDUT} \end{aligned} \tag{18}$$

$$\begin{aligned} Q_{mG@DUT} &= Q_{VG@REF}.b_{G\_REFtoDUT}\cdot\rho_{G@DUT} \\ &\quad + Q_{VO@REF}.b_{O\_REFtoDUT}.R_{OG2\_REFtoDUT}\cdot\rho_{OG\_REFtoDUT} \\ &\quad + Q_{VW@REF}.b_{W\_REFtoDUT}.R_{WG2\_REFtoDUT}\cdot\rho_{WG\_REFtoDUT} \end{aligned} \tag{19}$$

With the variable ρ_{xy_AtoB} representing the density of the phase x at conditions A becoming Y at conditions B

7.6. Density Evaluation at Flowmeter Conditions

In this final section, it is presented the way of calculating the density at DUT conditions based on the value of density from the oil, water, and gas phases flowing through each single-phase reference flowmeters. The way to understand the calculation of the density at the DUT is to come back to the concept of mass. The total mass of oil at DUT conditions will be based on the mass of oil at the reference flowmeters minus the mass of gas coming out from the oil (dissolved gas), and the mass of oil/condensate coming from the change of pressure and temperature, mainly producing some condensate. The following equation can be written:

$$M_{O@DUT} = M_{O\_REFtoDUT} - M_{G\_REFtoDUT} + M_{O\_REFtoDUT} \tag{20}$$

This equation can be rewritten as follow:

$$M_{O@DUT} = \rho_{O@REF}.V_{O@REF} - \rho_{OG\_REFtoDUT}.V_{OGout\_REFtoDUT} + \rho_{GC\_REFtoDUT}.V_{GCin\_REFtoDUT} \tag{21}$$

The first term on the right side of this equation is fully defined, the second term to evaluate the volume of gas coming out of the oil can be obtained by writing the following equation:

$$\begin{aligned} \frac{V_{OGout\_REFtoDUT}}{V_{O@SC}} &= \frac{V_{Gtotal\_REFtoSC}}{V_{O@SC}} - \frac{V_{Gtotal\_REFtoDUT}}{V_{O@SC}} \\ &= GOR_{2\_REFtoSC} - GOR_{2\_DUTtoSC} \\ &= R_{GO2\_REFtoSC} - R_{GO2\_DUTtoSC} \end{aligned} \tag{22}$$

To establish the volume of condensate coming from the volume of the gas from reference condition to DUT condition, the following expression could be established:

$$\begin{aligned}\frac{V_{OGout\_REFtoDUT}}{V_{O@SC}} &= (\frac{V_{G\_REFtoSC}}{V_{O@SC}} - \frac{V_{G\_DUTtoSC}}{V_{O@SC}}).CGR_{2REFtoDUT} \\ &= (GOR_{1\_REF} - GOR_{1\_DUT}).CGR_{2REFtoDUT} \\ &= (R_{GO1\_REFtoSC} - R_{GO1\_DUTtoSC}).R_{CG2\_REFtoDUT}\end{aligned} \quad (23)$$

Finally, the density of oil at DUT conditions is divided by the volume of oil at DUT conditions, and combining the produce equations we obtain:

$$\begin{aligned}\rho_{o@DUT} = \frac{M_{o@DUT}}{V_{o@DUT}} &= \rho_{o@REF} \cdot \frac{V_{o@REF}}{V_{o@DUT}} \\ &- \rho_{OG\_REFtoDUT} \cdot (R_{GO2\_REFtoSC} - R_{GO2\_DUTtoSC}) \cdot \frac{V_{o@SC}}{V_{o@DUT}} \\ &+ \rho_{GC\_REFtoDUT} \cdot (R_{GO1\_REFtoSC} - R_{GO1\_DUTtoSC}).R_{GC2\_REFtoDUT} \cdot \frac{V_{o@SC}}{V_{o@DUT}}\end{aligned} \quad (24)$$

Or

$$\begin{aligned}\rho_{o@DUT} = b_{o@DUT} \cdot (\rho_{o@REF} \cdot \frac{1}{b_{o@REF}} &- \rho_{OG\_REFtoDUT} \cdot (R_{GO2\_REFtoSC} - R_{GO2\_DUTtoSC}) \\ &+ \rho_{GC\_REFtoDUT} \cdot (R_{GO1\_REFtoSC} - R_{GO1\_DUTtoSC}).R_{CG2\_REFtoDUT})\end{aligned} \quad (25)$$

It can be seen from the equation (25) is that the density of oil calculated at the DUT conditions require access to 9 additional parameters with their associated uncertainty.

The same equation can be established for the water and the gas as presented:

$$\begin{aligned}\rho_{W@DUT} = b_{W@DUT} \cdot (\rho_{W@REF} \cdot \frac{1}{b_{W@REF}} &- \rho_{WG\_REFtoDUT} \cdot (R_{GW2\_REFtoSC} - R_{GW2\_DUTtoSC}) \\ &+ \rho_{GW\_REFtoDUT} \cdot (R_{GW1\_REFtoSC} - R_{GW1\_DUTtoSC}).R_{WG\_DUT})\end{aligned} \quad (26)$$

The calculation of the density of gas at DUT conditions is presented in appendix A, leading to the following expression:

$$\begin{aligned}\rho_{g@DUT} = b_{g@DUT} \cdot (\rho_{g@REF} \cdot \frac{1}{b_{g@REF}} &+ \rho_{OG\_REFtoDUT} \cdot (\frac{1}{R_{GO2\_REFtoSC}} - \frac{1}{R_{GO2\_DUTtoSC}}) \\ &- \rho_{GC\_REFtoDUT} \cdot (R_{GC2\_REFtoSC} - R_{GC2\_DUTtoSC}) \\ &+ \rho_{WG\_REFtoDUT} \cdot (\frac{1}{R_{GW2\_REFtoSC}} - \frac{1}{R_{GW2\_DUTtoSC}}) \\ &- \rho_{GW\_REFtoDUT} \cdot (R_{GW2\_REFtoSC} - R_{GW2\_DUTtoSC}))\end{aligned} \quad (27)$$

7.6.1. with Live fluids and Uncertainty Evaluation

To summarise, we have this set of six equations which represent the volumetric flowrate for oil, water, and gas; and the density for each phase at DUT condition:

$$Q_{VO@DUT} = Q_{VO@REF}.b_{O\_REFtoDUT} + Q_{VG@REF}.b_{g\_REFtoDUT}.R_{GO2\_REFtoDUT} \quad (28)$$

$$Q_{VW@DUT} = Q_{VW@REF}.b_{W\_REFtoDUT} + Q_{VG@REF}.b_{g\_REFtoDUT}.R_{GW2\_REFtoDUT} \quad (29)$$

$$\begin{aligned} Q_{VG@DUT} &= Q_{VG@REF}.b_{G\_REFtoDUT} + Q_{VO@REF}.b_{O\_REFtoDUT}.R_{OG2\_REFtoDUT} \\ &\quad + Q_{VW@REF}.b_{W\_REFtoDUT}.R_{WG2\_REFtoDUT} \end{aligned} \quad (30)$$

$$\begin{aligned} \rho_{o@DUT} &= b_{o@DUT}.(\rho_{o@REF}\cdot\frac{1}{b_{o@REF}} - \rho_{OG\_REFtoDUT}\cdot(R_{GO2\_REFtoSC} - R_{GO2\_DUTtoSC}) \\ &\quad + \rho_{GC\_REFtoDUT}\cdot(R_{GO1\_REFtoSC} - R_{GO1\_DUTtoSC}).R_{CG2\_REFtoDUT}) \end{aligned} \quad (31)$$

$$\begin{aligned} \rho_{W@DUT} &= b_{W@DUT}.(\rho_{W@REF}\cdot\frac{1}{b_{W@REF}} - \rho_{WG\_REFtoDUT}\cdot(R_{GW2\_REFtoSC} - R_{GW2\_DUTtoSC}) \\ &\quad + \rho_{GW\_REFtoDUT}\cdot(R_{GW1\_REFtoSC} - R_{GW1\_DUTtoSC}).R_{WG2\_REFtoDUT}) \end{aligned} \quad (32)$$

$$\begin{aligned} \rho_{g@DUT} &= b_{g@DUT}.(\rho_{g@REF}\cdot\frac{1}{b_{g@REF}} + \rho_{OG\_REFtoDUT}\cdot(\frac{1}{R_{GO2\_REFtoSC}} - \frac{1}{R_{GO2\_DUTtoSC}}) \\ &\quad - \rho_{GC\_REFtoDUT}\cdot(R_{GC2\_REFtoSC} - R_{GC2\_DUTtoSC}) \\ &\quad + \rho_{WG\_REFtoDUT}\cdot(\frac{1}{R_{GW2\_REFtoSC}} - \frac{1}{R_{GW2\_DUTtoSC}}) \\ &\quad - \rho_{GW\_REFtoDUT}\cdot(R_{GW2\_REFtoSC} - R_{GW2\_DUTtoSC})) \end{aligned} \quad (33)$$

Without going in-depth of each equation (28) to (33), the propagation of error on the right side of the different equations increases with the most significant amount of parameters to take into account to calculate the uncertainty of densities and flowrates at DUT conditions. This is also demonstrating what was said earlier that the performance of the reference flowmeters (i.e. Coriolis) as claimed by the manufacturer would be affected by contamination, the line pressure, and the ratios of dissolution of one phase inside the other, but also the drift, equation fit uncertainty, and the standard deviation of the average. It is the entire set equation with the associated uncertainty, and some challenges to obtain them coming from the selected equation of state that will determine the overall claim of uncertainty at the DUT conditions.

The different expressions, written before, are general and including the different effects like steam, condensate, or gas dissolved in oil and water. If the composition of the gas as no CO2 nor H2S and the temperature of the fluid is kept low enough to avoid some steam, and there is no condensate, it is possible to rewrite the equations as presented below:

$$Q_{VO@DUT} = Q_{VO@REF}.b_{O\_REFtoDUT} + Q_{VG@REF}.b_{g\_REFtoDUT}.R_{GO2\_REFtoDUT} \quad (34)$$

$$Q_{VW@DUT} = Q_{VW@REF}.b_{W\_REFtoDUT} \quad (35)$$

$$Q_{VG@DUT} = Q_{VG@REF}.b_{G\_REFtoDUT} + Q_{VO@REF}.b_{O\_REFtoDUT}.R_{OG2\_REFtoDUT} \quad (36)$$

$$\rho_{o@DUT} = b_{o@DUT}.(\rho_{o@REF}\cdot\frac{1}{b_{o@REF}} - \rho_{OG\_REFtoDUT}\cdot(R_{GO2\_REFtoSC} - R_{GO2\_DUTtoSC})) \quad (37)$$

$$\rho_{W@DUT} = \rho_{W@REF} \cdot \frac{b_{W@DUT}}{b_{W@REF}} \qquad (38)$$

$$\rho_{g@DUT} = b_{g@DUT} .(\rho_{g@REF} \cdot \frac{1}{b_{g@REF}} + \rho_{OG\_REFtoDUT} .(\frac{1}{R_{GO2\_REFtoSC}} - \frac{1}{R_{GO2\_DUTtoSC}}) \qquad (39)$$

However, having access to these 6 output parameters (density of each phase and flowrate of each phase), it is then possible to obtain the water-liquid ratio (WLR), Condensate Gas Ratio (CGR), gas Volume Fraction (GVF), hydrocarbon flowrates, water volume fraction (WVF), oil volume fraction (OVF), and some key parameters such as Froude numbers, or Lockhart-Martinelli.

7.6.2. with Inert fluids and Uncertainty Evaluation

The last question to address now is: what will be the interest or value to use inert or immiscible gas in some specific conditions? The gas used for establishing the performance of MPFM and WGFM is, in general, nitrogen. By definition, this gas is based on only one molecule and can be associated with a perfect gas or similar behavior, considering the compressibility factor "Z". This will simplify the determination of the density of the gas at different line pressure and temperature significantly. However, it was said earlier that when the pressure is increasing, some of the nitrogen will be dissolved inside the oil in the reality, and in such case we are facing the same problem, as presented earlier (Equations 34 to 39) which are assuming there is no condensate, steam, H2S, and CO2 presence inside the third party facility.

However, there is a significant advantage in the use of nitrogen gas in that the modeling is coming from the fact that no tuning of the equation of state (EOS) is necessary, and, therefore, proper uncertainty on gas dissolution and compressibility factor can be established based on the numerous papers available on this subject. This will lead to proper traceability, which is essential for establishing the correct performance.

What was highlighted earlier was also that the dissolution of the nitrogen, as soon as the line pressure is large enough (>5 bara), is the same quantity of gas dissolved in percentage at line conditions, and the differential pressure is small enough for fair pressure variation 3 to 9 bar. This means that GOR2 can be considered constant. Under such cases, it is possible to simplify the setup equation and rewrite them as presented below:

$$Q_{VO@DUT} = Q_{VO@REF} .b_{O\_REFtoDUT} = Q_{VO@REF} \frac{b_{O\_REFtoSC}}{b_{O\_DUTtoSC}} = Q_{VO@REF} \frac{b_{O@REF}}{b_{O@DUT}} \qquad (40)$$

$$Q_{VW@DUT} = Q_{VW@REF} .b_{W\_REFtoDUT} = Q_{VW@REF} \frac{b_{W@REF}}{b_{W@DUT}} \qquad (41)$$

$$Q_{VG@DUT} = Q_{VG@REF} .b_{G\_REFtoDUT} = Q_{VG@REF} \cdot \frac{b_{g@REF}}{b_{g@DUT}} \qquad (42)$$

$$\rho_{o@DUT} \approx \rho_{o@REF} \cdot \frac{b_{o@DUT}}{b_{o@REF}} \qquad (43)$$

$$\rho_{W@DUT} = \rho_{W@REF} \cdot \frac{b_{W@DUT}}{b_{W@REF}} \quad (44)$$

$$\rho_{g@DUT} \approx \rho_{g@REF} \cdot \frac{b_{g@DUT}}{b_{g@REF}} \quad (45)$$

The new set of equations is more straightforward to apply than the earlier ones (equation from 34 and 39), and it is built only through the knowledge of the shrinkage factors, the volumetric flowrate, and the density for each phase at reference conditions. It is interesting to note that the simplification of the problem is possible if values recorded at reference conditions and DUT conditions should be converted to standard conditions before the comparison. It is the entire PVT that should be considered. By using Nitrogen and immiscible fluid, it is possible to quickly make a comparison, with minimum additional uncertainty, and establish the performance of the flowmeter at DUT conditions as expected by manufacturers of flowmeters. On the other side, if we want to look at the overall uncertainty associated with some PVT package comparison, this analysis should be done in such cases at standard conditions. It could be concluded that the benefit of using what we will call here semi-immiscible fluid leads to establishing the performance of the flowmeter in one case properly, but also at standard conditions, as expected by the end-user (oil and gas company).

7.7. Practical Case

Before concluding, let's look at some specific cases associated with the nitrogen, and what are the challenges that third-party facilities are facing to get low uncertainty, or high-quality performance, for the respective clients (Manufacturers and Oil and Gas Operators). Obviously, it is an order of magnitude more challenging for third party facilities using natural gas. As related earlier, the composition of the gas may change with time, and this needs to be considered, which will affect the density of the gas, but also the solubility with the other phases. We propose to look at firstly the solubility inside the oil and demonstrate one of the statements written in the previous section and secondly to highlight the challenges associated with Z factor, which is representing the deviation for the nitrogen versus the law established for a perfect gas. In simple words, the compressibility factor.

7.7.1. Effect of the solubility of the nitrogen

This section is showing some results associated with the gas dissolved inside the oil. As mentioned earlier, Nitrogen solubility can reach quickly the maximum value, which is a fundamental characteristic by selecting N_2. The figure below (10) is showing in percentage the concentration of gas dissolved inside the oil (refined oil) versus line pressure. A semilogarithmic scale is used for this figure on the X-axis; two sets of data are represented. The first one is representing the amount of gas dissolved inside the oil, which will come out with variation of the line pressure of around 1 bar; it could be noted that whatever the pressure from around 2 bara up to 15 bara as presented, there is no more than 1.5 ft^3 of gas coming out for one barrel of oil and this is relatively constant whatever the line pressure. The second curve is representing the quantity of gas coming out of oil with the line pressure variation around 9 bar. In this case, we are close to roughly 10 ft^3 per barrel of oil, and this is relatively constant from 10 to 60 bara, and a slight increase can be noted up to 150 bars, but this is quite marginal with not more than 1.8 ft^3 additional of volume of gas coming out for one barrel of oil. This justifies the statement said earlier that looking at the comparison of the performance of MPFM or WGFM against references; this can be done in a very straightforward manner at line conditions. This also shows that the calculation at standard conditions with the highest level of accuracy should account for this dissolution of gas inside the oil.

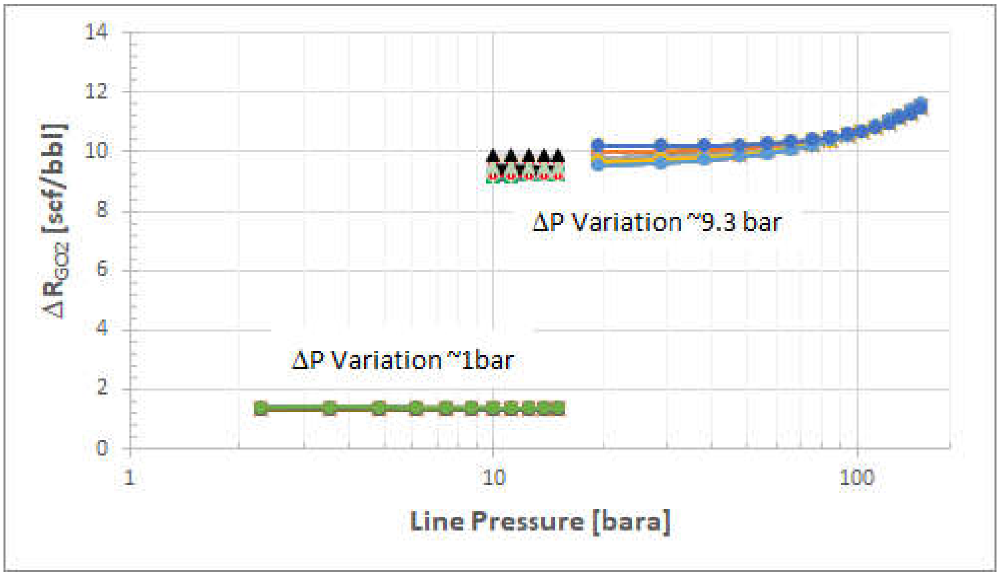


Figure 10: Gas dissolution in oil versus line pressure and pressure variation between the reference and DUT conditions.

To be thoughtful about the challenges associated with the dissolution of oil, figure (11) is showing a subset of data recorded and published about the dissolution of gas inside refined oil. A few models (EOS) have been tuned to the set of data; the purpose is to show that multiple regression techniques (EOS) are available. However, it is important to challenge the one selected. All the equations of states (EOS) are producing numbers, and the challenge is to find the one which is closer to reality (measurement). Therefore, it is critical to do take a significant set of measurements to achieve the proper uncertainty of any parameters used for calculation of the performance and associated uncertainty; in this case, of the flowmeters.

It should be noted that all packages using equation of states (EOS) are not providing any uncertainty associated with the output parameters. To the knowledge of the authors, only two packages can provide such a statement, which are DPPR and PPDS. Both have been developed and based on the same initial database over the last 40 years. The latter is produced and available commercially through the National Engineering Laboratory (NEL). Said in other words, the parameters are provided with an uncertainty that is related to the measurements used to establish the key parameters used in the EOS.

NEL has some experts in fluid properties and the figure (11), we have used different equations of state, which are cubic based EOS, and useful in predictions of non-polar species phase behaviour, particularly for gas components like CO_2 and N_2 Valderrama–Patel–Teja (VPT), Soave–Redlich–Kwong (SRK), Peng-Robinson (PR), and cubic-plus-association (CPA). Thus, the performance of the final cubic equations of state should not be expected to perform well for polar relatively symmetric systems. On the other hand, SAFT based equations of state, such as perturbed-chain statistical associating fluid theory (PC-SAFT), are suitable for modeling of polar liquids (mixtures) phase behavior. Therefore, associating mixtures and multiphase behavior, especially for multicomponent systems, represent the limit of cubic based EOS and association models. For example, those belonging to the SAFT family (e.g. PC-SAFT) are expected to perform better for such complex systems and with fewer adjustable parameters. One of the other significant differences between SAFT based models and cubic EOS is the difference in the function/type of binary interaction parameters (BIPs) for each EOS, which would significantly affect on the modeling results particularly when we aim to predict the solubility behavior over the range of pressure & temperature.

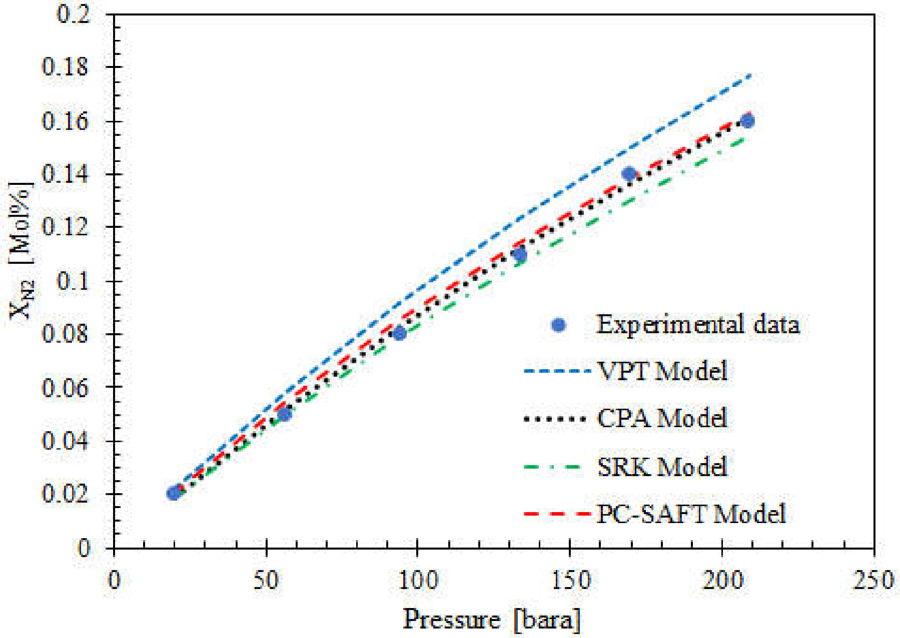


Figure 11: Fit modeling of the dissolution of Nitrogen into refined oil. Data recorded at 10°C

Again, this is a subset of data presented, but it can be established that the TC – SASLD and CDA model are the best solution to model the nitrogen dissolved inside refined oil. A significant increase in uncertainty will result in other models. There is a need for lot of work in collecting data from the literature or costly specific studies, but they are necessary; all this information is required to determine the appropriate EOS to use with suitable justification. Thee evidence and justification should be available through documents and open to any audit. This will also show the challenges that third-party labs need to face to establish the overall uncertainty of the references at either flow metering reference conditions and the DUT conditions. It is believed today to be so straight forward, but this is minimizing the effort on the development of accurate and fair associated uncertainty. This could lead in the future to some severe liability when the spread of the MPFM and WGFM in fiscal metering and fiscal allocations are common, and worst with the large size of flowmeter from 6 to 8-inch and above.

7.7.2. Calculation of the Compressibility Factor of the nitrogen

In one of the previous sections, we have been introducing a way of calculating the density of the nitrogen at different line pressures and temperatures. This was expressed by the following formula (46), where Z is a compressibility factor of the nitrogen:

$$\rho_{N_2} = \frac{P_{@lc[Pa]}}{Z}\frac{R}{T_{@lc[K]}} = \frac{Z_{@sc}}{Z}\frac{T_{@sc[K]}}{T_{@lc[K]}}\frac{P_{@lc[Pa]}}{P_{@sc[Pa]}} \qquad (46)$$

The uncertainty claimed on the Z factor is ±0.02% on the entire range of pressure and temperature of the given facility. This was possible by first collecting more than 120 values of the compression factor, and second, modeling the compressibility factor versus pressure and temperature with the formula (47) as presented below. The value of the "a" factors are not given inside this document because they are irrelevant for this discussion, which is to highlight that to gain 1/10 or 1/100 of percent, considerable effort needs to be spent to investigate all the possible errors. As often said "the Devil is in the details". The "a" factors have 12 significative digits.

$$\begin{aligned} Z = {} & 1 + P_{[bara]}\cdot\left(a_1\left(\frac{300}{T_{[K]}}\right)^{3/4} + a_2\left(\frac{300}{T_{[K]}}\right)^{5/4} + a_3\left(\frac{300}{T_{[K]}}\right)^{3}\right) \\ & + P_{[bara]}\cdot\left(\frac{300}{T_{[K]}}\right)\cdot\left(a_4\left(\frac{300}{T_{[K]}}\right)^{1} + a_5 P_{[bara]}\cdot\left(\frac{300}{T_{[K]}}\right)^{1/2} + a_6 P_{[bara]}\cdot\left(\frac{300}{T_{[K]}}\right)^{3/4}\right) \end{aligned} \qquad (47)$$

8. CONCLUSIONS

This paper has been written with the aim to provide an overview for the third-party laboratory on how to calculate uncertainties at reference conditions, and how to bring this information to device under test (DUT) conditions, considering current mass transfer that could be happening versus line pressure and temperature variation.

This paper is also showing to the end-user and manufacturers of multiphase and wet gas flowmeters that a lot of calculations, researches, and associated experiments need to be completed by the third-party laboratory to be able to claim a given number in terms of uncertainty at DUT conditions. It was shown that for some specific cases, the reason for making a comparison at line conditions between the DUT and reference flowmeter conditions is preferable to minimize the overall uncertainty of the entire systems. This may not be the position of the end-user, which may require to look at the performance of the flowmeter at standard conditions and wish to see how the flowmeter is performing from line conditions to standard conditions. However, in this case, it is almost compulsory to provide the PVT package to each data point to be able to make a proper comparison, and this leads to little interest.

It is evident that the claim of uncertainty from the manufacturer of single-phase flowmeters cannot be used as such uncertainty for multiphase or wet gas facilities. This is nothing to do with the quality of the manufactured product or the process of calibration, but it is related to the fact that the uncertainty in the calibration provided by the manufacturer of single-phase flowmeters is ideal with usual water or air as a reference fluid. The single-phase flowmeter, however, will be used with different types of fluids, and the line pressure and temperature will be changing, affecting the performance of this reference flowmeter in-service conditions.

As mentioned through this report, it is not only the calibration uncertainty that should be taken into account but also the equation fit uncertainty, the drift uncertainty, the average value uncertainty (standard deviation on the measurement) which is linked with some unstable or natural variation on the flow conditions and lead to some spread that should be taken into account. These uncertainty sources should be accounted for as a minimum. Additional, perhaps significant, sources of uncertainty will also be relevant for each particular case that should be accounted for.

It could be necessary to add the response of the single-phase reference flowmeter contamination (presence of undesired phases inside the main expected one); but also, the validation of the composition of the different so-called single-phase fluid, which will exchange some mass between the different phases versus line pressures and temperatures.

Finally, a way of calculating and presenting the propagation of uncertainty has been proposed inside this document, some other presentations are possible but what is interesting in this table concept is to be able to note quickly and clearly what are the main parameters affecting the overall uncertainty, and then give an opportunity to work individually on these spotted parameters to significantly reduce the overall uncertainty.

9. ACKNOWLEDGMENT

The work presented in this document is representing the compilation of multiple documents available either in the literature or in NEL, discussions, expertise, and affirmations.

The authors would like to especially thank Richard Harvey, who has been a significant contributor through these large amounts of documentation, and some referenced below, and Edris Joonaki through some of the information provided in the PVT sections. Any errors present in this document are solely the responsibilities of the authors.

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11. APPENDIX A

The calculation of the density of the gas at DUT conditions is presented here below; the idea is to start from the mass of gas and then add and subtract all the mass transfer that happens with the oil and water phases. We can write the mass of gas as follows:

$$\begin{aligned} M_{g@DUT} = {} & \rho_{g@REF}.V_{g@REF} + \rho_{OG\_REFtoDUT}.V_{OGout\_REFtoDUT} - \rho_{GC\_REFtoDUT}.V_{GCin\_REFtoDUT} \\ & + \rho_{WG\_REFtoDUT}.V_{WGout\_REFtoDUT} - \rho_{GW\_REFtoDUT}.V_{GWin\_REFtoDUT} \end{aligned} \tag{48}$$

To reach the density at the DUT conditions, we divide by the volume of gas at DUT, as presented below:

$$\begin{aligned} \frac{M_{g@DUT}}{V_{g@DUT}} = {} & \rho_{g@REF}\cdot\frac{V_{g@REF}}{V_{g@DUT}} + \rho_{OG\_REFtoDUT}\cdot\frac{V_{OGout\_REFtoDUT}}{V_{g@DUT}} - \rho_{GC\_REFtoDUT}\cdot\frac{V_{GCin\_REFtoDUT}}{V_{g@DUT}} \\ & + \rho_{WG\_REFtoDUT}\cdot\frac{V_{WGout\_REFtoDUT}}{V_{g@DUT}} - \rho_{GW\_REFtoDUT}\cdot\frac{V_{GWin\_REFtoDUT}}{V_{g@DUT}} \end{aligned} \tag{49}$$

We can rewrite the equation to highlight some specific parameters:

$$\begin{aligned} \rho_{g@DUT} = {} & \rho_{g@REF}\cdot\frac{V_{g@REF}}{V_{g@SC}}\frac{V_{g@SC}}{V_{g@DUT}} \\ & + \rho_{OG\_REFtoDUT}\cdot\frac{V_{OGout\_REFtoDUT}}{V_{g@SC}}.b_{g@DUT} - \rho_{GC\_REFtoDUT}\cdot\frac{V_{GCin\_REFtoDUT}}{V_{g@SC}}.b_{g@DUT} \\ & + \rho_{WG\_REFtoDUT}\cdot\frac{V_{WGout\_REFtoDUT}}{V_{g@SC}}.b_{g@DUT} - \rho_{GW\_REFtoDUT}\cdot\frac{V_{GWin\_REFtoDUT}}{V_{g@SC}}.b_{g@DUT} \end{aligned} \tag{50}$$

and

$$\begin{aligned} \rho_{g@DUT} = {} & \rho_{g@REF}\cdot\frac{V_{g@REF}}{V_{g@SC}}\frac{V_{g@SC}}{V_{g@DUT}} + \rho_{OG\_REFtoDUT}\cdot\frac{V_{OGout\_REFtoSC} - V_{OGout\_DUTtoSC}}{V_{g@SC}}.b_{g@DUT} \\ & - \rho_{GC\_REFtoDUT}\cdot\frac{V_{GCin\_REFtoSC} - V_{GCin\_DUTtoSC}}{V_{g@SC}}.b_{g@DUT} \\ & + \rho_{WG\_REFtoDUT}\cdot\frac{V_{WGout\_REFtoSC} - V_{WGout\_DUTtoSC}}{V_{g@SC}}.b_{g@DUT} \\ & - \rho_{GW\_REFtoDUT}\cdot\frac{V_{GWin\_REFtoSC} - V_{GWin\_DUTtoSC}}{V_{g@SC}}.b_{g@DUT} \end{aligned} \tag{51}$$

which leads to this following equation:

$$\begin{aligned} \rho_{g@DUT} = {} & b_{g@DUT}.(\rho_{g@REF}\cdot\frac{1}{b_{g@REF}} + \rho_{OG\_REFtoDUT}.(R_{OG2\_REFtoSC} - R_{OG2\_DUTtoSC}) \\ & - \rho_{GC\_REFtoDUT}.(R_{GC2\_REFtoSC} - R_{GC2\_DUTtoSC}) + \rho_{WG\_REFtoDUT}.(R_{WG2\_REFtoSC} - R_{WG2\_DUTtoSC}) \\ & - \rho_{GW\_REFtoDUT}.(R_{GW2\_REFtoSC} - R_{GW2\_DUTtoSC})) \end{aligned} \tag{52}$$

Usually, we use the concept of gas dissolved in oil and the inverse; therefore, we can rewrite the equation finally as presented below:

$$\begin{aligned}\rho_{g@DUT} = b_{g@DUT}.(\rho_{g@REF}.\frac{1}{b_{g@REF}} + \rho_{OG\_REFtoDUT}.(\frac{1}{R_{GO2\_REFtoSC}} - \frac{1}{R_{GO2\_DUTtoSC}}) \\ - \rho_{GC\_REFtoDUT}.(R_{GC2\_REFtoSC} - R_{GC2\_DUTtoSC}) + \rho_{WG\_REFtoDUT}.(\frac{1}{R_{GW2\_REFtoSC}} - \frac{1}{R_{GW2\_DUTtoSC}}) \\ - \rho_{GW\_REFtoDUT}.(R_{GW2\_REFtoSC} - R_{GW2\_DUTtoSC}))\end{aligned} \tag{53}$$

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