Laboratory and Field Validation of a New Coriolis Metering Concept for Better Measurement Uncertainty, Reliability and Process Insight

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Abstract

Coriolis mass flowmeters are widely accepted in various industries for the great performance of density and mass flow rate measurements. Not only do they play a critical role in O&G custody transfer applications, but also an increasingly important role in addressing the new challenges and applications related to the energy transition where the highest accuracy and reliability is also required. Analogous to multi-beam Ultrasonic flowmeters, a new measuring concept based on Coriolis principle has been developed with a metering system that consists of two individual Coriolis meters arranged in parallel for the incoming flow in the system. There are numerous advantages of this arrangement, among which reducing measurement uncertainty, increasing reliability and gaining greater process insight are the most significant ones. The statistic theory has shown that for a total measurement equally divided by two sub-measurements of two independent measuring devices, the measurement uncertainty caused by random errors is reduced by a factor of square root of 2 for the combined total measurement. This rule applies to the Zero Point and repeatability performance of the metering system. Taking the advantage of independently measuring the same or similar fluid parameters twice, the measurement reliability is enhanced by cross-checking the two sets of measured parameters. For certain special cases, such as transient disturbance of entrained gas that often exists under real process conditions, the corresponding negative impact can even be mitigated or eliminated by utilizing the undisturbed measured parameter set from the two. The spacial arrangement of the two Coriolis meters makes it useful to monitor the measured fluid parameters such as two sets of densities, flows and temperatures for obtaining the knowledge of the special distribution of fluid parameters, gaining greater process insight.

A critical step has been the validation of the theoretical advantages in third-party laboratories and in the field. A test was done for the Zero Point stability of the metering system under various temperatures, pressures and viscosities at NEL using the EPAT facility. The measurement results suggested that the Zero Point deviations of the two Coriolis meters followed a random probability and tended to cancel each other to certain degree, leading to a reduced Zero Point deviation for the complete metering system. Repeatability and reproducibility tests were done both at NEL EPAT and at Euroloop oil rigs with provers, showing good and consistent results. Recognizing most hydrocarbon markets trade on a volumetric basis rather than mass, the advantages the design brings towards density measurement are discussed and measurement data is presented across varying fluid densities and viscosities. In step with the growing importance of gaseous fluids to the evolving energy markets, the influence the novel design has on performance in gas applications is described and measurement data in gases is also presented. Furthermore, an interesting phenomenon has been captured during the flow stabilization phase before proving at Euroloop that transient disturbance of gas bubbles could be present, and very often disturbed only one meter at the same time, which enables the possibility to remediate the effect of transient disturbances. The same phenomenon took place in field tests of the metering system, indicating the high probability of the occurrence. In this paper, the laboratories data from the NEL EPAT rig, Euroloop rig, *pigsar* rig, and H&D Fitzgerald as well as the data from field applications are presented and analysed to validate the theoretical analysis.

1. Introduction

Coriolis mass flowmeters are widely used in various industries, such as Oil & Gas, Chemicals and Food & Beverage, thanks to their high reliability and accuracy in mass flow rate and density measurements. On the other hand, the expectations from users are steadily increasing regarding the need to meet the requirements of critical applications, for example, custody transfer or proving in the Oil & Gas industry, where a very stable Zero Point and good meter repeatability are needed. In the meanwhile, a good measurement reliability remains important in all Coriolis applications. Modern Coriolis meters do provide some enhanced diagnostic functions for performing meter health checks, for example, Endress+Hauser Promass Coriolis meters are equipped with Heartbeat Technology to ensure that the meter measuring tubes and transmitter are in good condition. However, in certain applications it may still be necessary that some simple means is available to users for verifying the validity of meter measurement results. Usually, a reliability check of a measurement involves comparing the measured value with the corresponding reference value. However, very often a reference value is not available, cannot easily be obtained or may not be accurate enough. In addition, the measuring point of the reference may not be the same as the meter installation point or operate under the same process conditions, for example when comparing fluid density with lab density measurements. Furthermore, it is certainly desired that a transient disturbance, which can occur under some operational conditions, can not only be detected for the purposes of measurement reliability, but also can be handled so that the influence on the meter measurement is minimized.

With the above challenges in mind, a novel Coriolis metering concept has been developed and realized in a single body of a Coriolis meter, which functions as a conventional Coriolis device to end users, but provides better measurement uncertainty, reliability and process insight.

2. “2 in 1” 4-tube meter

2.1 Mechanical configuration

Fig. 1 shows different views of the “2 in 1” 4-tube meter. It consists of two independent tube pairs, namely the inner tube pair and the outer tube pair, each of which is analogous to a conventional dual-tube Coriolis meter. Some further details are depicted in Fig. 2, where a front view of such a device is shown. As can be seen, each tube pair has its own driver, sensors and couplers, so that flow and density measurements are performed separately without any mechanical or electrical coupling to the other tube pair. At the flow splitters, e.g. at the outlet side of the meter, flows in the two tubes of a tube pair join in the first small chamber and then meet the flow from the other tube pair in the second big chamber, which is shared by the two tube pairs. Therefore, the two tube pairs only have mechanical connection via the inlet and outlet flow splitters, which are outside the effective measuring section of a Coriolis meter. Furthermore, the two tube pairs share the same housing, flanges and the meter transmitter, making the appearance of the device the same as a conventional dual-tube Coriolis meter. The “2 in 1” 4-tube meter is available in the sizes 6" (DN150), 8" (DN200) and 10" (DN250), serving as a size extension of the existing Endress+Hauser Promass Q series.

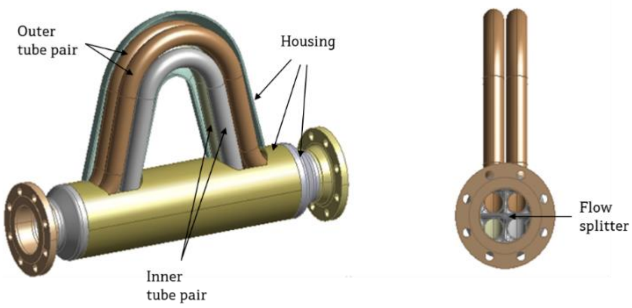

Figure 1: “2 in 1” 4-tube meter, left: ISO view; right: side view.

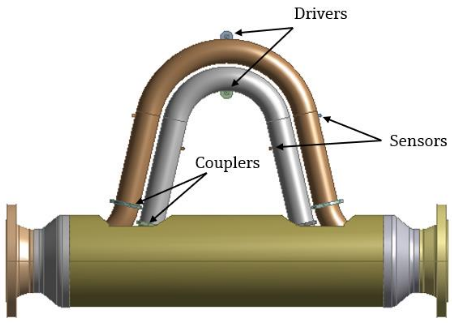

Figure 2: “2 in 1” 4-tube meter, front view.

2.2 Functional description

Being decoupled, the two tube pairs have their own working modes, as depicted in Fig. 3. Their couplers are carefully designed to be at different positions, so that the working frequencies of the two tube pairs are not the same, namely

$$f_i \neq f_o \,, \quad (1)$$

where the subscript $_i$ and $_o$ represent the inner tube pair and the outer tube pair respectively. As each tube pair gives a set of measured parameters, the final outputs of the whole device are calculated accordingly. The total mass flow is thus given by

$$\dot{m} = \dot{m}_i + \dot{m}_o \, . \qquad (2)$$

The effective density is handled automatically and intelligently according to actual process conditions. Under normal conditions, it is calculated by

$$\rho = \frac{\rho_i + \rho_o}{2} \, . \qquad (3)$$

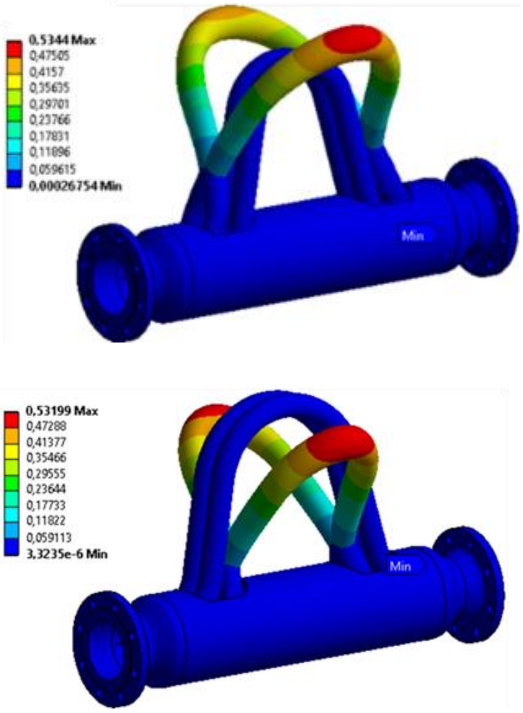

Figure 3: Two independent working modes; top: outer tube pair; bottom: inner tube pair (simulation, shown in exaggerated form).

Proper consideration has been given to other measured process parameters of the device (e.g. temperature), which can thus be used in exactly the same manner as in the case of a conventional Coriolis meter.

2.3 Technical advantages

There are several technical advantages for flow and density measurements based on this metering concept, among which reducing measurement uncertainty, increasing reliability and gaining greater process insight are the most significant ones.

2.3.1 Zero Point Stability

It is well known that Zero Point stability is a critical performance factor for a Coriolis mass flowmeter and remains as one of the most significant challenges for developing high-performance Coriolis meters. Zero Point stability is defined as the variation of the indicated flowmeter output when there are zero flow conditions present at the meter and its value has a direct influence on the accuracy of the measurement. There are numerous factors that contribute to the Zero Point stability of a device. In practice, the ability of a meter to retain the same Zero Point during long-term operation is most important. As the measuring tube oscillation is the basic mechanism for flow measurement, it is naturally of special importance for a good Zero Point stability that the mechanical oscillation of the device is decoupled from the process environment. This task is typically accomplished through careful design of the sensor part (i.e. the measuring tubes and the accessories on the tubes such as couplers) and via the stiffness of meter housing and mechanical connections (shown in Fig. 1) that contain the residual force and the deformation at the tube ends.

A high-performance Coriolis dual-tube meter has been introduced in [1] and [2], where the design of the sensor part has been highly optimized with the help of numerical simulation. Nevertheless, it is still essential that the housing suppresses the remaining movement and deformation at the ends of the measuring tubes. This is explained in Fig. 4, where the top picture shows the static situation of one tube end without oscillation, whilst the bottom picture depicts the simulation result of tube oscillation without housing in an exaggerated form. It can be seen that the two tube ends have both displacement and deformation away from the original positions and the original round shape, although the magnitude is small in reality.

This displacement and deformation should be suppressed by the housing of the meter. The greater stiffness of the housing, the better decoupling of this motion from the environment. On the other hand, the housing of a Coriolis meter cannot be built with excessive dimensions just to increase the stiffness, because the consequent increase in size, mass and weight can prevent reasonable transportation, installation and handling of such a device in a process system. However, the intelligent “2 in 1” design with different working frequencies of the “two meters” inside makes this possible.

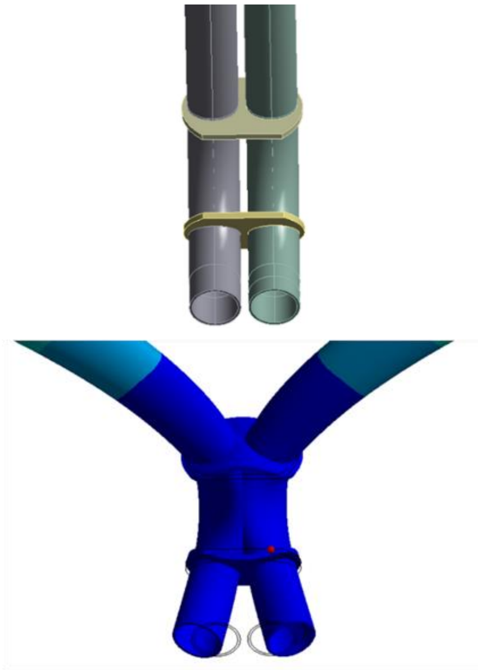

Figure 4: Top: tube end region in static situation without oscillation; bottom: simulation result for the same region undergoing a tube oscillation (shown in exaggerated form).

As shown in the top diagram in Fig. 5, it is assumed that the reaction force that a tube end applies to the housing, also referred to as residual force, has the magnitude of F for a conventional dual-tube meter. Ideally, the housing would contain this force completely if it were infinitively stiff. However, due to the finite stiffness of the housing in reality, the energy of this disturbance can be transmitted from the meter to the environment, and then be reflected back to the tube oscillation in the meter, impacting the Zero Point stability of the meter because it has exactly the same frequency as the meter. In the case of a smaller size dual-tube meter, the corresponding residual force is certainly smaller. However, its housing is also weaker due to the reduced dimensions, leading to a Zero Point stability relative to the corresponding measurement range of this meter size similar to the bigger dual-tube meter.

Compared with a conventional dual-tube meter of the same size, the force of each tube end of a 4-tube meter is naturally smaller because of the smaller tube dimension and has the magnitude of approximately 0.5F in this case. If the two frequencies of the two tube pairs in the 4-tube meter were the same, the combined force would be the same as the conventional dual-tube meter. However, the two tube pairs have different frequencies and are separated by a sufficient distance, which means that the two oscillation systems are isolated from each other with respect to the frequency domain and the corresponding signal processing. For each individual system, only a periodic disturbance exactly at its working frequency can affect the Zero Point. The periodic residual force from the other system, which has a different frequency, thus has no effect on this system. Hence the disturbing residual force only has the magnitude of 0.5F for each individual system, but the housing remains as strong as that for the corresponding conventional dual-tube meter. In other words, the strong housing can contain and isolate the individual tube oscillations of the two tube pairs better in the case of a “2 in 1” 4-tube meter, leading to an improved Zero Point stability of the system.

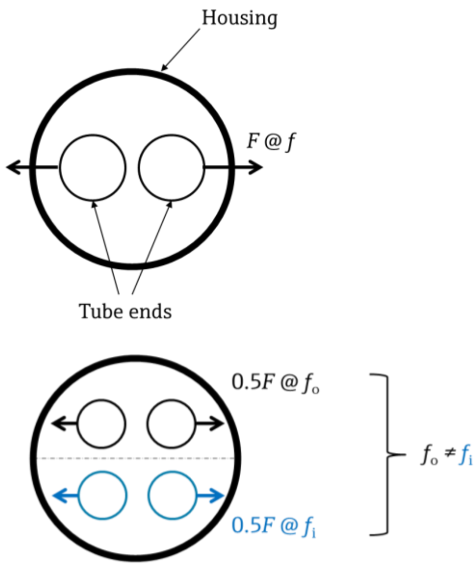

Figure 5: Top: the forces of the tube ends applying to the housing in a conventional dual-tube meter; bottom: the smaller forces in a “2 in 1” 4-tube meter.

2.3.2 Zero Point stability and repeatability

Statistical theory shows that for a total measurement divided equally into two sub-measurements of two independent measuring devices, the measurement uncertainty caused by random errors is reduced by a factor $\sqrt{2}$ for the combined total measurement [3]. This rule applies to the Zero Point and the repeatability performance of the metering system.

Fig. 6 depicts the schematics of two measuring systems for comparison. The top diagram shows a flow measurement with a conventional dual-tube meter (Meter A) for a total flow rate of X, whilst the bottom diagram shows a “2 in 1” 4-tube meter (consisting of two meters of a smaller size, i.e. 2 * Meter B) for measuring the same amount of flow. Assuming the uncertainties that are introduced by random errors for the two types of meters, namely Meter A and Meter B, are both ±0.05 % of the flow rate measured for certain period, the measurement uncertainty of Meter A is then directly equal to ±0.05 %. However, following the statistic procedure, the measurement uncertainty of the metering system that consists of 2 * Meter B is calculated by

$$\frac{\pm\sqrt{(0.05\%*0.5X)^2+(0.05\%*0.5X)^2}}{X} = \pm 0.035\%. \qquad (4)$$

Thus, for random errors the “2 in 1” 4-tube metering system benefits from the two independent measurements performed by two physically “different” meters and gains an improvement of a factor of $\sqrt{2}$, compared with a conventional dual-tube meter, since random errors tend to cancel each other out.

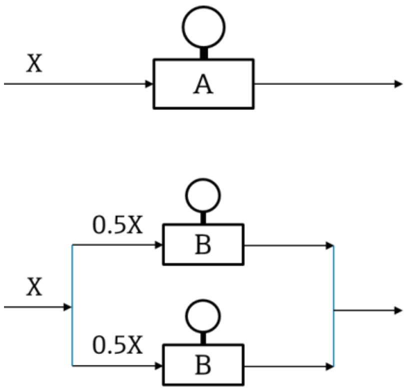

Figure 6: Top: flow measurement with a conventional dual-tube meter; bottom: flow measurement with a “2 in 1” 4-tube meter.

Fig. 7 proves the improvement in repeatability and stability of the Zero Point on the basis of simulated mass flow signals. In this example we assume an unrealistic high standard deviation of 10 % for an individual dual-tube meter in order to make the scattering visible in the graphs. As can be seen, the combination (blue) of the two inner (red) and outer (green) dual-tube pairs results in only 7 % standard deviation compared to 10 % of the conventional dual tube meter (black).

In practice, it is the stability of the Zero Point rather than the level of the absolute value, which is of importance to end users. This is because a Zero Point adjustment is recommended for applications whose process conditions or fluid properties are very different to the reference conditions under which the factory Zero Point was determined. However, after the adjustment, it is expected that the meter retains the same Zero Point, even if the process conditions or fluid properties vary within a reasonable range. In reality, the Zero Point of a Coriolis meter can still shift slightly within the specified range in a “random” manner as process conditions or fluid properties change.

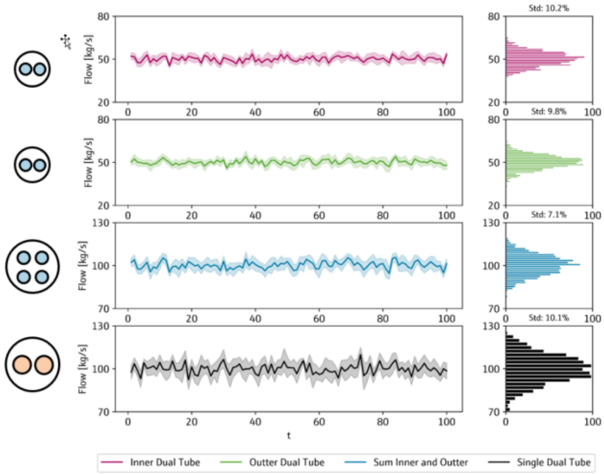

Figure 7: Comparison of repeatability between a conventional dual-tube meter and a “2 in 1” 4-tube meter of the same size (red and green: small inner and outer dual-tube meters; blue: combined “2 in 1” 4-tube meter; black: conventional dual-tube meter).

For instance, when a Zero Point adjustment is performed, there might be very tiny gas bubbles in the process medium. The distribution of those bubbles in the meter measuring tube, which directly impacts the sign and the magnitude of the meter Zero Point, is “random”. Furthermore, the superposition of numerous tiny anti-symmetric imperfections (e.g. slight ovality of a measuring tube) in combination with small variations in process conditions (e.g. temperature or pressure) or fluid properties (e.g. fluid viscosity or density) result in a “random” nature of the Zero Point drift. The final Zero Point of the “2 in 1” 4-tube meter is the sum of those of the two individual meters. Because the imperfections of the two measuring tube pairs are statistically independent, the “2 in 1” 4-tube metering system again takes the statistical advantage that the sum of the two Zero Points of the two individual and independent meters in the system remains in a smaller range compared with a conventional dual-tube meter, when process conditions or fluid parameters vary. This is analogous to the calculation example given by Fig. 6 and Eq. (4).

Regarding the measurement advantage for meter repeatability, which is a critical performance parameter for applications such as proving, it becomes slightly more complex, as the measurement repeatability is not only dependent on the Coriolis sensor part, but also on the meter transmitter that consists of signal processing part and I/O. Although the “2 in 1” 4-tube meter has two separate sensor parts and signal processing, some parts of the meter transmitter are shared. If the “bottle neck” for the measurement repeatability came from the meter transmitter, e.g. the I/O for the data transmission, the “2 in 1” concept would not help to improve the repeatability performance. However, it has been observed that in practice, some “bottle neck” does come from process conditions, e.g. micro-bubbles in the process medium or significant flow noise, which directly impact the sensor part of the meter rather than the transmitter, leading to a reduced performance for repeatability that may not be acceptable, e.g. during a proving. Under such a condition, the “2 in 1” 4-tube metering system improves the repeatability performance due to the fact, that these disturbances are random. The statistical advantage described in Fig. 6 and Eq. (4) therefore improves the repeatability by a factor of $\sqrt{2}$.

2.3.3 Throughput and flow velocity in the measuring tube

In Fig. 8, the theoretical maximum flow area is drawn for a dual-tube meter and a 4-tube meter respectively, in the same cross-sectional area with respect to the nominal diameter of the connecting pipe that the meter is designed for. A geometrical calculation suggests that the 4-tube design can theoretically offer an up to +36 % greater flow area than the dual-tube design. In reality, the maximum increase cannot be realized in the 4-tube design. Nevertheless, up to +25 % more flow area has been produced in 4-tube meters, which leads to a corresponding increased throughput of the meters. This also means that the pressure loss of a 4-tube meter can be significantly lower than a 2-tube meter with the same nominal size for the same flow rate. Furthermore, the increased flow area of a 4-tube meter results in a lower flow velocity in the measuring tubes for the same flow rate, which in turn results in a special advantage for certain applications, where a high flow velocity in measuring tubes becomes critical, e.g. due to the risk of abrasion/erosion/corrosion or electrostatic charge.

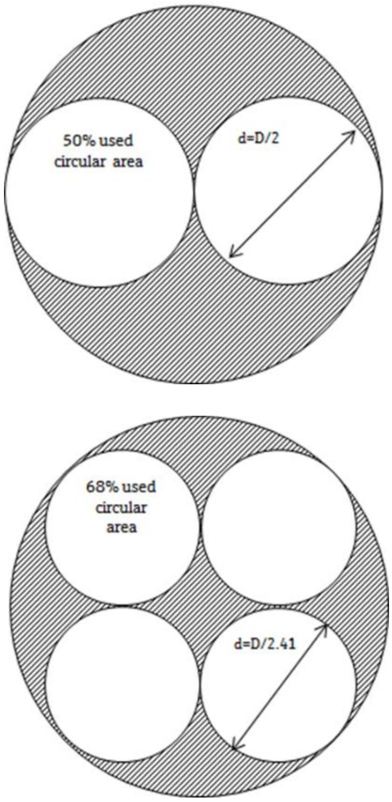

Figure 8: Comparison of flow area between a conventional dual-tube meter and a 4-tube meter.

2.3.4 Transient Disturbance Handling

In many Oil & Gas applications, transient disturbances can occur, e.g. due to temporarily entrained gas. One of the detection methods for such a disturbance is introduced in [4], with the entrained gas index that is based on the density fluctuation of a medium under such a condition. Although the bubble detection function already provides useful information regarding the measurement reliability, it is a more advanced and useful step that such disturbance can be handled to fulfill the requirement of certain applications. For example, in Oil & Gas industry, volume flow rate of an oil product is very often of primary interest, requiring a precise density measurement of the liquid oil phase. When entrained gas is present, it reduces the measured density of a Coriolis meter as the mixture density of the gas-liquid two-phase fluid drops due to the presence of the gas bubbles. Therefore, the reported volume flow rate from the Coriolis meter is that of the two-phase mixture (instead of the oil), which is not really the value needed by users.

The “2 in 1” 4-tube meter can offer an obvious advantage for certain entrained gas applications. For example, for a horizontal installation as shown in Fig. 9, transient bubbles very often tend to flow on top due to the buoyancy effect, if it is not operating under a very severe entrained gas condition. Since the “two meters” perform the measurements and diagnosis independently, the metering system can capture the situation that one meter is suffering from entrained gas disturbance while the other meter is measuring under a liquid-only condition. Therefore, the system uses the liquid density from the undisturbed meter to replace the measured density from the disturbed meter, resulting in a volume flow rate measurement only for the liquid phase. It should be noted that this “substitution” uses a real-time measured value other than a “held value” from the history, offering an apparent advantage over the method of “hold last good value”, which suffers from the risk of using a very incorrect historical measurement.

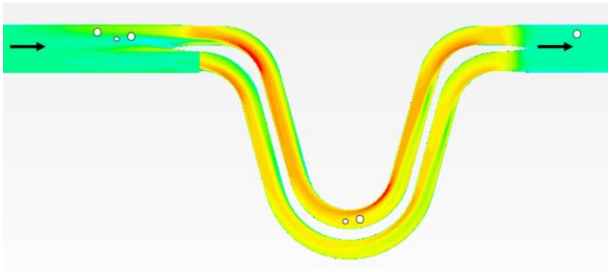

Figure 9: Transient bubbles flowing through a “2 in 1” 4-tube meter.

2.3.5 Potential for obtaining an enhanced process insight

The new platform of the “2 in 1” 4-tube meter offers further possibilities for an advanced analysis of the measurement reliability, the meter status and the process conditions. Therefore, three additional diagnostic parameters, which are given below in Eqs. (5) - (7), are defined as service parameters that help in such an analysis.

$$d\rho = \rho_o - \rho_i \qquad (5)$$

$$dT = T_o - T_i \qquad (6)$$

$$\%\dot{m}_o = \frac{\dot{m}_o}{\dot{m}_o + \dot{m}_i} \qquad (7)$$

The parameter $d\rho$ in Eq. (5) gives the measured density difference between the two tube pairs. Under ideal conditions, this value should be very small, e.g. below 0.5 kg/m^3. However, some upset conditions can lead to a deviation of this value, either transiently, or stably, depending on the actual type of the disturbances. For example, a transient entrained gas can lead to an instantaneous fluctuation of $d\rho$, while unevenly distributed build-up or abrasion/corrosion in the two tube pairs can cause a stable, gradual increase or decrease of this value. It should be noted that the tube bending radii of the two tube pairs are significantly different, as shown e.g. in Fig. 9, giving rise to different flow velocity profiles due to the centrifugal effect. Therefore, the rates of build-up accumulation or abrasion/corrosion effect in the two tube pairs can indeed be different and offers a good chance for the observation of the measurement density difference.

The second parameter dT in Eq. (6) shows the measured temperature difference between the two tube pairs. Under ideal conditions with a sufficient flow velocity, this value should be very small, e.g. below 0.2 °C. A deviation of this value might suggest a temperature stratification in the process medium, especially for a horizontal installation.

The third parameter $\%\dot{m}_o$ in Eq. (7) shows the ratio of the measured mass flow of the outer tube pair to the measured total mass flow. It basically represents the mass flow distribution into the two tube pairs. Under ideal conditions with a sufficient flow velocity, e.g. greater than 1 m/s with respect to the nominal pipe size, this value is close to 50% because all tubes are of the same diameter, although the lengths of the two tube pairs differ slightly. In practice, a significant and stable deviation of this value, for instance to about 25 % or 75 %, may indicate a clogging of one measuring tube if the total mass flow is sufficiently high. It should be noted that there might be other influence factors that change the flow distribution, such as entrained gas or non-ideal upstream installation conditions. Therefore, such an analysis should be combined with other measured parameters of the device or further process information and cannot be always generalized.

Nevertheless, these additional diagnostic parameters open the door and provide the potential for obtaining an enhanced process insight. The exploration of this potential and provision of application experience, together with the application experts of the vendor, is encouraged.

2.3.6 Multi-Frequency Technology (MFT) for suspended bubbles

In Subsection 2.3.4, the method of Transient Disturbance Handling is developed for temporary free bubbles. In practice, suspended bubbles or micro-bubbles can exist in Oil & Gas applications.

An innovative technology, namely MFT, has been introduced in [1] and also realized in the corresponding products. The “2 in 1” 4-tube meter inherits this technology for the compensation of the resonator effect caused by this type of bubble, and even benefits from using smaller tubes compared with those in a conventional dual-tube meter.

It can be concluded from [1] that the resonator effect not only depends on the fluid properties such as Gas Void Fraction (GVF) and pressure, but also on the measuring tube size. A bigger measuring tube causes a greater resonator effect in a quadratic manner, leading to more significant measurement errors for density and mass flow. Therefore, the necessity to have this compensation, especially for large size Coriolis meters, is especially high. The “2 in 1” 4-tube meter therefore offers an advantage in using smaller tubes for this compensation, because the magnitude of the error to be corrected is also lower.

2.3.7 Other advantages of using smaller tubes

As depicted in Fig. 8, four smaller tubes are used in a “2 in 1” 4-tube meter, whilst a conventional dual-tube meter with the same meter size has two bigger tubes. This brings some performance advantages to the 4-tube concept.

The first advantage goes to the performance of pressure sensitivities for mass flow and density measurements. It is obvious that the bending stiffness of a smaller tube is less influenced by pressure than that of a bigger one with the same tube wall thickness.

Regarding the Reynolds Number effect for flow measurement, there have been many research activities carried out in the past. It has been pointed out in [5] that a “slender” measuring tube is advantageous for this effect and results in a smaller measurement deviation for mass flow. Therefore, keeping the same effective tube length, the tube with a smaller diameter has a greater slenderness, which leads to a better performance for the Reynolds Number effect.

3. Laboratory and field validation

In this section, laboratory and field test results are presented to validate the technical advantages of the “2 in 1” 4-tube concept.

3.1 Zero Point Stability tests at NEL

It is known that process and medium conditions such as pressure, temperature and viscosity can have an effect on the Zero Point of a Coriolis meter. The motivation of this series of the tests was to observe the Zero Point deviations of a DN200 “2 in 1” 4-tube meter, including the deviations of each individual meter and the total metering system, under various process and medium conditions. TÜV SÜD National Engineering Laboratory (NEL) was selected to perform such a test because oils with different viscosities (in the Oil Rigs at NEL) and various process conditions, such as different pressures and temperatures (in the EPAT Rig at NEL), could be provided for the test.

The test results have shown that the Zero Point deviations under various conditions from those under the reference condition (i.e. water @ 20 °C, 4 barg) were satisfactorily within the specification of such a device. In order to be independent of different definitions of Zero Point on market and only focus on the corresponding advantage of the “2 in 1” 4-tube concept, the unit of the test results given in Table 1 has been removed. The test numbers from 1 to 10 correspond to different medium and process conditions. For some test points, a repetition was made at a totally different time and the results suggested a very good reproducibility of the device under test.

Table 1: Static Zero Point tests of a “2 in 1” 4-tube meter at NEL

Test No.	Fluid/Process condition	Zero Point of outer tube pair	Zero Point of inner tube pair	Zero Point of “2 in 1” meter
1	Velocite (40 cSt)	0.2	0.0	0.2
2	Aztec (600 cSt)	-0.8	1.1	0.3
3	EPAT (20°C, 5 barg)	0.7	-0.5	0.2
4	EPAT (20°C, 45 barg)	1.2	-0.5	0.7
5	EPAT (80°C, 45 barg)	0.7	-0.5	0.2
6	EPAT (80°C, 25 barg)	0.2	-0.5	-0.5
7	EPAT (80°C, 5 barg)	-0.8	0.0	-0.8
8	EPAT (40°C, 45 barg)	-0.3	0.5	0.2
9	EPAT (40°C, 25 barg)	-0.3	0.5	0.2
10	EPAT (40°C, 5 barg)	-0.8	0.0	-0.8
exp. unc.		**0.67**	**0.68**	**0.53**

As shown by the last row in the Table 1, the expanded uncertainty (k = 2) of the 10 listed Zero Point deviations of the outer tube pair is 0.67 and that of the inner tube pair is 0.68. However, the final Zero Point of the whole system, which is the sum of the two individual Zero Points, does not show an accumulation effect for the uncertainty. Instead, it is even slightly smaller than that for each of the two individual meters, again suggesting a factor of $\sqrt{2}$. As can be seen in Table 1, the Zero Point deviations can be classified as “random”, and the “2 in 1” metering concept has shown the advantage of the “cancelling” effect for those “random” deviations in this test, leading to a better Zero Point stability.

3.2 Oil test at Euroloop

At Euroloop in the Netherlands, two “2 in 1” 4-tube meters were measured with 20 cSt oil and compared with the prover. The test was done almost for the whole span of the measurement range for these meters. For each flow rate, three measurement points were taken in order to determine the mean mass flow deviation of the meters and the repeatability, defined by the calculation rule maximal error minus minimal error for all points of the same flow rate.

As can be seen in Table 2, all deviations were satisfactorily within the specification of these devices. Regarding the Zero Point stability, the measurement results at low flow rates, especially at the lowest flow rate, have shown that the measurement errors introduced by the Zero Point deviation were almost invisible and manifested a very stable Zero Point during the whole process. The exceptionally good repeatability of the meters attracted particular attention.

Table 2.1: Proving result at Euroloop for a 6” 4-tube meter with 20 cSt oil (Certificate number EH.200918.0838.12.1.A.R1).

Indicated flow [ton/h]	Deviation [%]	Repeatability [%]
16.42	-0.011	0.003
25.70	-0.005	0.010
43.06	0.008	0.003
72.30	0.024	0.005
119.81	0.027	0.001
189.68	0.018	0.002
307.70	-0.005	0.005
506.74	0.003	0.013

Table 2.2: Proving result at Euroloop for a 10” 4-tube meter with 20 cSt oil (Certificate number EH.200914.1406.12.2.A.R1).

Indicated flow [ton/h]	Deviation [%]	Repeatability [%]
50.81	-0.078	0.008
78.52	-0.001	0.016
127.57	0.023	0.007
213.80	0.037	0.003
341.28	0.027	0.003
556.32	-0.004	0.001
896.87	-0.026	0.011
1453.86	-0.022	0.002

It was observed with interest during the preparation phase for the test that the function of transient disturbance handling had become active for the moment when gas bubbles were temporarily flowing through the meter. The recorded internal measurement signals are plotted in Fig. 10, where the density measurement of the inner tube pair (orange) shows a sudden drop because bubbles typically travel in the upper part of the flow due to the buoyancy effect. At that moment, the algorithm could detect this disturbance coming from gas bubbles well and correctly handle it, resulting in a final density output for liquid phase only (grey).

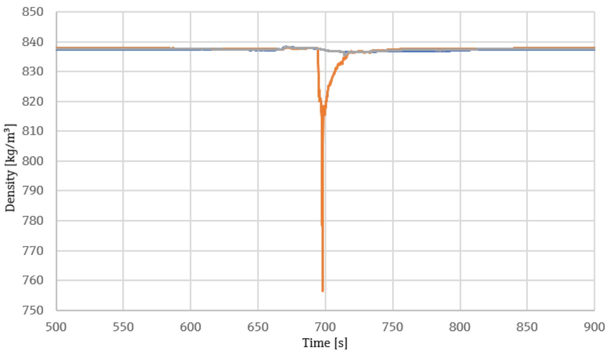

Figure 10: Validation of transient disturbance handling for density (orange: inner tube pair; blue: outer tube pair; grey: final output).

3.3 Natural gas tests at pigsar

All three sizes of the “2 in 1” 4-tube meter have been qualified at the high pressure natural gas rig *pigsar* in Germany. As an example, in Table 3 the deviation and uncertainty of a 10” 4-tube meter are listed over rising mass flow rates at 43 bara and 18 °C. The low Deviation (%) of mass flow across the full flow range indicates remarkably good linearity and Zero Point stability of the meter. U_{meter} (%) is the expanded standard uncertainty of the tested 4-tube meter, determined on the basis of n = 5 repeats at each flow rate, multiplied by Student-t-factor(n)/$n^{0,5}$, with a probability of 95 %. Based on this data a good repeatability even at high flow rates can be stated for the “2 in 1” 4-tube concept. Comparable results were achieved for lower pressures around 20 bara and the other meter sizes as well.

Table 3: Typical mass flow deviation and repeatability of a 10” 4-tube meter tested with high pressure natural gas at *pigsar* (Certificate number 19212/2021).

Qi / Qmax	Qi (kg/h)	Reynoldsnumber	Deviation (%)	n	Umeter (%)
0,02	3320,10	0,38 *10⁶	-0,06	5	0,11
0,10	14885,56	1,69 *10⁶	-0,08	5	0,02
0,21	32175,13	3,65 *10⁶	-0,09	5	0,04
0,46	69278,28	7,86 *10⁶	0,05	5	0,02
0,67	100102,61	11,37 *10⁶	0,05	5	0,05
0,81	121212,45	13,77 *10⁶	0,04	5	0,04
0,99	148911,62	16,88 *10⁶	0,20	5	0,06

3.4 Density test at H&D Fitzgerald

An 8” 4-tube meter was tested at the UKAS accredited laboratory H&D Fitzgerald in the UK. Beside air, the meter was filled with a number of liquids in a density range from 750 kg/m³ up to 1250 kg/m³ and with viscosities up to 1400 mPa·s, covering fluid properties of the most typical hydrocarbons. The meter was stabilized in a thermostated heat chamber at 25 °C. It was found that the temperature indicated by the “2 in 1” 4-tube meter matched the reference temperature better than 1 mK for all fluid samples. With the exception of the Lube460, the densities of the liquids used were determined by comparing them with nominally identical liquids which had been through a ISO17025 accredited hydrostatic weighing rig. The density of the Lube460 was determined by pyknometry, which is outside the ISO17025 accreditation. As indicated by the error bars in Fig. 11, the expanded uncertainty (k = 2) in meter error for all tested fluids, except the high viscous Lube460, typically was ±0.025 kg/m³. As can be seen in Fig. 11, without onsite adjustment all density deviations were well within the density specification of ±0.2 kg/m³. Recognizing most hydrocarbons are traded on a volumetric basis, this demonstrated density performance across density and viscosity translates directly to exceptional in field volume flow performance as well as highly stable meter factors (e.g derived from in field meter proving), especially in the case of multi-product pipelines.

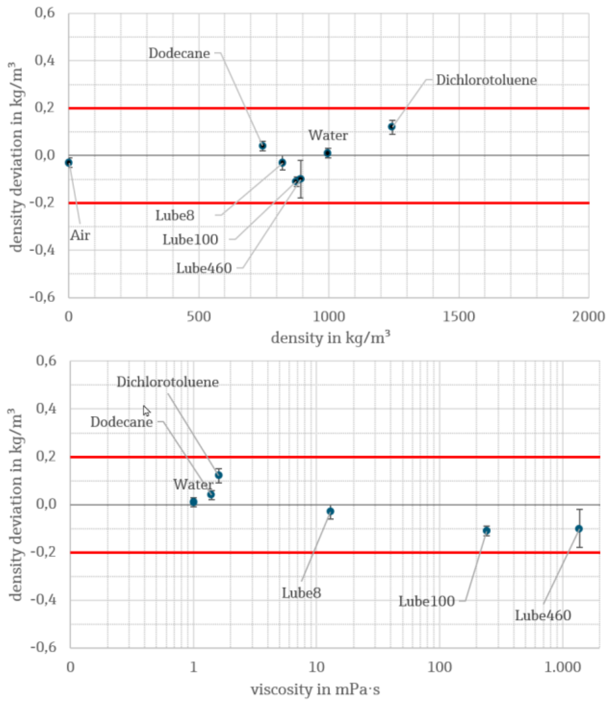

Figure 11: Density deviation of different fluids at H&D Fitzgerald for a 8” 4-tube meter; top: density over density; bottom: density over viscosity (Certificate number 17728).

3.5 Entrained gas field test

To qualify the entrained gas performance and to validate the MFT compensation for suspended entrained gas, a “2 in 1” 4-tube meter was tested in a field application and compared with a conventional dual-tube meter of a comparable size. The medium in this application, which has a similar form to the one shown in Fig. 12, can contain up to 45 % suspended bubbles or foam in volume under atmospheric pressure. The measured densities were compared with the reference measurements, which were made by manual sampling. Since the gas content in the product is of interest, the GVF under atmospheric pressure, GVF_a, was derived from the measured density of the meter, ρ_m, together with the knowledge of the liquid phase density ρ_l and the process pressure p, as given by

$$GVF \approx 1 - \frac{\rho_m}{\rho_l}, \quad (8)$$

$$GVF_a \approx GVF \cdot p. \quad (9)$$

The test result given in Table 4 suggests very good agreement between the derived GVF_a from the meter measurement and the reference GVF from the manual sampling, considering the high uncertainties in performing both GVF measurements under such a challenging condition. For comparison, the result from the conventional dual-tube meter deviated significantly from the reference, indicating the advantage of the "2 in 1" 4-tube meter for entrained gas applications.

Figure 12: Suspended entrained gas with GVF up to 40 % under atmospheric pressure (the photo and the name of the test medium are not shown here by request of the customer).

Table 4: Comparison for the density measurements

GVF measured in the "2 in 1" 4-tube	Process pressure p [bara]	GVF_a (under atmospheric pressure)	Reference GVF measured by manual sampling (averaged)
20.5 %	2.2	45 %	43 %

4. Conclusion

A novel Coriolis metering concept that combines two independent sets of measurements has been introduced. There are numerous advantages of this arrangement, among which reducing measurement uncertainty, increasing reliability and gaining greater process insight are the most significant ones. Statistical theory has shown that for a total measurement consisting of two independent sub-measurements, the measurement uncertainty caused by random errors is reduced by a factor of the square root of 2 for the combined total measurement. This rule applies to the Zero Point and repeatability performance of the metering system. Taking advantage of independently measuring the same or similar fluid parameters twice, the measurement reliability is enhanced by cross-checking the two sets of measured parameters. For certain special cases, such as transient disturbance of entrained gas that often occurs under real process conditions, the corresponding negative impact can even be mitigated or eliminated by utilizing the undisturbed measured parameter set of the two. The spacial arrangement of the two Coriolis meters makes it useful to monitor the measured fluid parameters such as the two measured densities, flows and temperatures, in order to obtain knowledge of the spacial distribution of fluid parameters, gaining greater process insight. The theoretical advantages have been validated in third-party laboratories and in the field. Some of these tests are described in this paper.

Notation

f	Frequency
$_i$	Subscript: inner tube pair
$_o$	Subscript: outer tube pair
$\dot{m}$	Mass flow rate
ρ	Density
T	Temperature
GVF	Gas Void Fraction
GVF_a	Gas Void Fraction under atmospheric pressure
p	Process pressure
ρ_m, ρ_l	Measured density, liquid density

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