

Extending Flow Measurement Capacity with the Straight-tube Coriolis Technology

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Abstract: Coriolis flowmeters had been mainly developed and used in line sizes less than DN100 (or 4-inch) because the size of the flow sensor itself could become too unwieldy and expensive for practical uses. This paper specifically reports the latest research and development of using the straight-tube Coriolis technology to extend flow measurement capacity to a high flow range. Design of the Coriolis flow sensor using a straight-tube configuration is firstly presented. Then, description of a special calibration procedure used in the manufacturer's gravimetric water flow rig is provided. Finally, an extensive test programme within internal facilities and other independent facilities is also reported. Test results verified straight-tube flowmeters' performance and showed a step forward in advancing the general Coriolis flowmetering technology.

Keywords: Coriolis flowmeter; flow measurement; flowmeter calibration.

1. Introduction

A Coriolis flowmeter is an electromechanical system which consists of a flow sensor and a converter. The flow sensor is the primary part which includes the internal measuring assembly, additional sensing devices, housing components, process connection and necessary wiring. In the past, Coriolis flowmeters had been mainly developed and used in line sizes less than DN100 (or 4-inch) because the size of the flow sensor itself could become too unwieldy and expensive for practical uses. Some recent developments have seen the extension of flow measurement capacity up to DN250 (or 10-inch) with either bent-tube or straight-tube technology.

A survey of three major Coriolis manufacturers' products is shown in Figure 1. The horizontal axis shows the diameter of each flow tube according to published technical data sheet, while the vertical axis shows the mass flow rate of water under 1bar pressure drop. Water flow rate under 1bar pressure drop is shown simply because it can be used as a common comparison reference. If logarithmic scales are used for both axes, it is then interesting to classify the flow range from 1t/hr to 1000t/hr as "normal flow range". Subsequently, the flow range above 1000t/hr can be classified as "high flow range", while the flow range from 0.001t/hr to 1 t/hr as "low flow range". Clearly, 1000t/hr appears to be a threshold point to define the high flow range and several manufacturers are capable of producing large Coriolis flowmeters in this flow range.

In order to extend flow measurement capacity to the high flow range above 1000t/hr, one of the most important tasks is to keep the flow sensor compact. Straight-tube flowmeters can offer an advantageous feature in terms of being compact. However, there are some technical challenges to extend the flow measurement capacity with the straight-tube Coriolis technology. This paper will specifically report the latest research and development work to address these challenges. Design of the Coriolis flow sensor using a straight-tube configuration will be firstly presented. Then, description of a special calibration procedure used in the manufacturer's gravimetric water flow

rig is provided. Finally, an extensive test programme within internal facilities and other independent facilities is also reported.

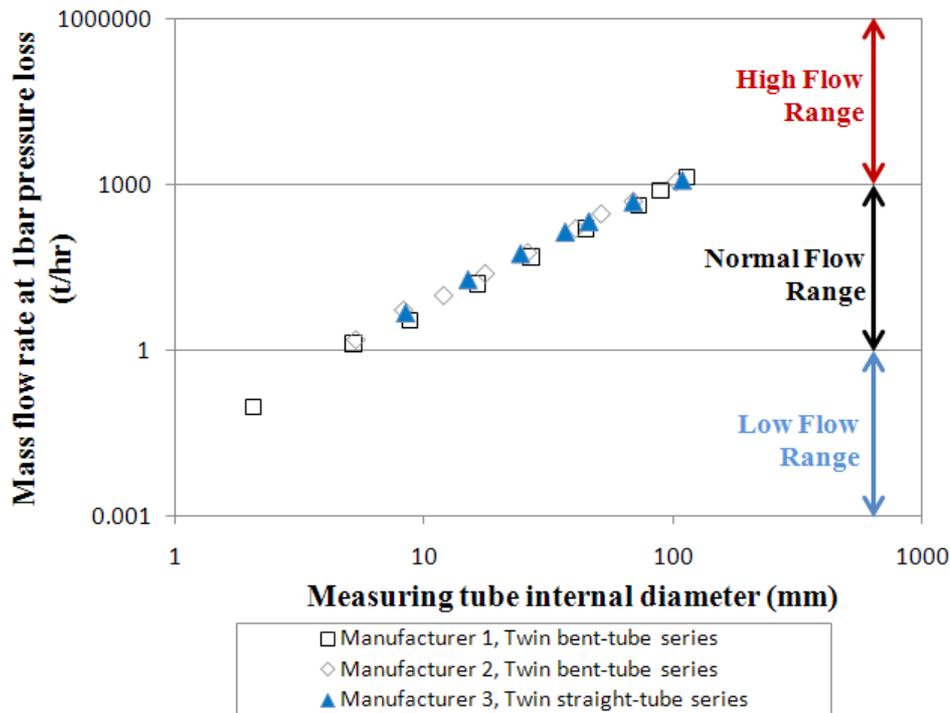


Figure 1: Flow range classification

2. Development of Straight-tube Coriolis Flow Sensors

2.1 Fundamental Theory

Coriolis flowmeters are one of the instruments based on the vibratory measuring principles. Mass flow can be measured using the so-called Coriolis principle, while density is measured using natural frequencies related to stiffness and mass. When flow is moving through a tube under controlled vibration, Coriolis force can create time delay between the inlet and outlet motion of the flow tube. This time delay t_d is an accurate indication of mass flow rate \dot{m} , and the relationship between them can be determined by a calibration procedure according to a traceable standard, for example accurate weigh scales. Because in reality there is always some sort of non-symmetric features in the flowmeter, the time delay at zero flow is not necessarily zero. Therefore, it has been a common practice to subtract this non-flow related time delay t_0 from the total time delay and calculate mass flow rate.

For vibratory measuring devices, their stiffness plays an important role in determining their characteristics. It is well known that elastic modulus of the tube material, stresses created by pressure or piping load and dimensional changes can affect structural stiffness. It is therefore desirable to consider these changes in the fundamental equations to calculate mass flow and density using Coriolis flowmeters.

The dynamics of fluid-tube interaction involved in Coriolis flow metering is a complex subject. One appropriate theory which can well describe the flow and density measurement principle is

the Timoshenko beam theory coupled with one dimensional axial flow [1]. If we consider the motion in the vibration plane and denote transverse deflection as u and rotation as θ at a specific point x and time t , the equation of motion without external force can be given as follows in (1) for a straight section of the flow tube,

$$\begin{aligned} (\rho_f A_f + \rho_p A_p) \frac{\partial^2 u}{\partial t^2} + 2\rho_f A_f v_0 \frac{\partial^2 u}{\partial x \partial t} + [\rho_f A_f v_0^2 - \sigma_0 A_p + \bar{p} A_f (1 - 2\nu\delta)] \frac{\partial^2 u}{\partial x^2} \\ + kGA_p \left(\frac{\partial \theta}{\partial x} - \frac{\partial^2 u}{\partial x^2} \right) = 0 \quad (1) \\ (\rho_f I_f + \rho_p I_p) \frac{\partial^2 \theta}{\partial t^2} - kGA_p \left(\frac{\partial u}{\partial x} - \theta \right) - [E + \sigma_0 - \bar{p} A_f (1 - 2\nu\delta) / A_p] I_p \frac{\partial^2 \theta}{\partial x^2} = 0 \end{aligned}$$

where the fluid is assumed to flow with a uniform and constant velocity v_0 , in a tube of internal area A_f , to have density ρ_f , and to have a rotary inertia I_f ; and where the conveying tube has an initial axial stress of σ_0 , mean internal pressure \bar{p} , density ρ_p , cross-sectional area of A_p , rotary inertia I_p , Young's modulus E , Poisson's ratio ν , shear modulus G , and shear correction factor k . δ is a constant: $\delta=1$ if axial motion is constrained (e.g. a clamped-clamped end condition), or $\delta=0$ if not constrained.

If we simply examine the individual terms in Equation (1), it actually includes most of the important factors involved in the measurement of Coriolis flowmeters, or generally speaking vibratory measuring devices. The term associated with $\partial^2 u / (\partial x \partial t)$ is the Coriolis term which indicates the effect of mass flow rate $\rho_f A_f v_0$, thus the principle of mass flow measurement through the Coriolis force. The term associated with $\partial^2 u / \partial t^2$ is the inertia term which indicates the effect of fluid density ρ_f , thus the principle of density measurement through the natural frequency. In addition, effects of other influences on the measurement are also considered. For example, the effects of material properties E and G and the effects of stresses σ_0 and \bar{p} together with dimensional variables are all included in this equation.

Equation (1) can be used to calculate the signals created by mass flow and density and predict how these signals will change when process conditions change. To calculate these, numeric methods have been particularly popular, which can be implemented by a direct damped method [2] or a linear damping model [3]. The calculations are very useful since they can be used at an early stage of the flow sensor development to make sure the signals are sufficient and less affected by process condition changes.

When the flow temperature changes, it affects the tube elastic modulus E . This is a well-known fact related to material properties and the relationship between the elastic modulus and temperature is available or can be determined by experiments. In a recent research [4], it was also shown that the thermal expansion of the tube material contributed a certain amount to the overall effect. Apart from the temperature effect, stresses can also influence the measurement as shown in Equation (1). These stresses can be created by thermal loads (e.g. temperature gradient) or mechanical loads (e.g. pressure). Since a flow tube is normally regarded as a shell structure, it needs predominantly two directions to fully define the stress condition: axial and circumferential. Although the effect of stresses on straight-tube and bent-tube Coriolis flowmeters is different as shown by a recent study [3] using both theoretical and experimental data, it is important to note this effect and consider it in the equations to calculate flow and density.

In summary, a comprehensive equation for mass flow rate measurement can be proposed as follows

$$\dot{m} = k_R \cdot (t_d - t_0) \cdot \alpha_m \cdot \beta_m \quad (2)$$

where k_R is the primary flow calibration factor determined under the reference calibration condition, α_m is the secondary flow calibration (or correction) factor which is a function of temperature and stresses of the flow tube, and β_m is the non-linear flow correction factor which is a function of mass flow rate itself and fluid density. Equation (2) is a practical and natural development of the fundamental governing Equation (1), which has a particular importance when developing Coriolis flowmeters. For density measurement, a similar equation can also be provided.

2.2 Design of the Large Size Straight-tube Flow Sensor

According to their flow tube shape, Coriolis flow sensors can be classified into bent-tube and straight-tube types. These two technologies are complementary to each other as they all have their own advantages. If the process temperature range is not extreme, straight-tube Coriolis flowmeters can offer some natural advantages such as compactness, less pressure drop, better drainability and less erosion in addition to high accuracy.

It is interesting to note that Equation (2) gives a guidance on the design of a flow sensor. The time delay signal $(t_d - t_0)$ provides the sensitivity against mass flow rate; the secondary correction function α_m indicates the effect of process condition changes; the non-linear correction function β_m shows other minor non-linear influences. Equation (1) can be used to optimise the flow tube parameters within a pre-defined set of constraints. It should be noted that the performance of flow measurement is not simply determined by the absolute magnitude of the time delay signal $(t_d - t_0)$. With the advance of modern electronic devices and software, phase difference or time delay obtained through digital signal processing has reached better precision. Actually, the stability of zero signal t_0 has becoming an increasingly important factor to define the performance of Coriolis flow measurement.

The stability of zero signal t_0 relies on the overall system including both mechanical and electronic parts. Balancing of the mechanical system is an essential means to maintain a high level of zero stability. It has also been found that not only the vibration along the drive plane but also vibrations over other directions should be considered. A well-balanced system has virtually no vibration escaping to the external world and thus less affected by external noises. A twin tube configuration provides a natural solution in particular for large size flowmeters. In order to assess a design, numerical simulations have been found particularly useful and cost-effective. Unlike Equation (1), this can be done purely within the structural domain, where fluid flows can be ignored initially. Commercially available finite element packages are capable of modelling small details.

Temperature sensors are normally available in a Coriolis flowmeter attached to the flow tube. They provide useful information when temperature deviates from its reference conditions. To correct for the effects of stresses, it is desirable to instantaneously detect the condition of the flow tube. Strain gauges attached to axial and circumferential directions of a tube can fully define its stress status.

As the result of a systematic development procedure, a twin straight-tube Coriolis flow sensor is shown in Figure 2, where the housing cylinder is deliberately removed to show the internal structure. A series of Coriolis flowmeters with nominal sizes greater than DN100 were developed. The largest one has a nominal size of DN250 and its mass flow rate is 1200t/hr under 1bar pressure drop for water flow, which is within the previously defined high flow range (>1000t/hr).

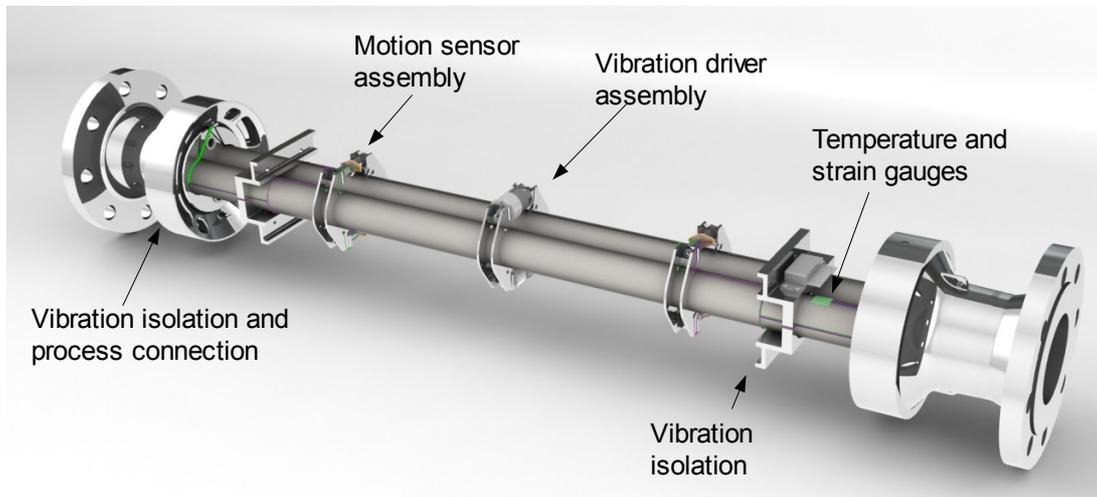


Figure 2: A twin straight-tube Coriolis flow sensor

3. Calibration of Straight-tube Coriolis Flowmeters

Calibration of large size Coriolis flowmeters has been done in a specially designed flow rig as shown schematically in Figure 3. Three water supply tanks are available with one of them maintained at room temperature and two others maintained at different elevated temperatures. The main pump is at upstream to the test section and it controls the flow rate together with a downstream control valve. After the control valve, the pipe line is split into two optional lines, batching or circulation. The batching line leads to the weigh scale, which is the primary calibration reference traceable to national standards. A secondary pump is also available in the rig to empty the weigh tank at the end of each batch run. The circulation line leads to a multi-beam ultrasonic meter, which can be used as reference meter for characterization or comparison test.

A standing start and stop calibration procedure has been adopted with this flow rig when flowing to the batching line. A computer controls each rig component and collects calibration data. A fully automated procedure can ensure repeatable start and stop conditions for batch tests. Since the total batch in terms of mass is the integration of mass flow rate over the batching duration, mass flow rate can be calibrated by comparing the flowmeter reading with the scale as a traceable reference. The calibration starts from establishing a reference condition and then collects repeated batch runs to determine the primary calibration factor k_R in Equation (2).

Subsequently, the secondary correction factor α_m can be determined by similar batching runs under non-reference conditions using the water supply tanks maintained at elevated temperatures. Deviations from the reference condition are detected by temperature sensors and strain gauges on the flow tubes. The secondary correction factor can then be obtained through a multi-variable

regression method. Alternatively, the secondary correction factor can also be obtained statistically according to past calibration runs.

The non-linear correction factor β_m is not always necessary since it is generally small and difficult to characterise. One of the effects is the so-called stability boundary effect [5] when the fluid velocity is high. This effect can be identified in Equation (1) since the term associated with $\partial^2 u / \partial x^2$ includes both v_0^2 and stiffness-related variables (σ_0 and \bar{p}). Another effect is that the transfer of Coriolis force between flow and tube at low Reynolds numbers is different from high Reynolds numbers. This effect may affect flow measurement of very viscous fluids.

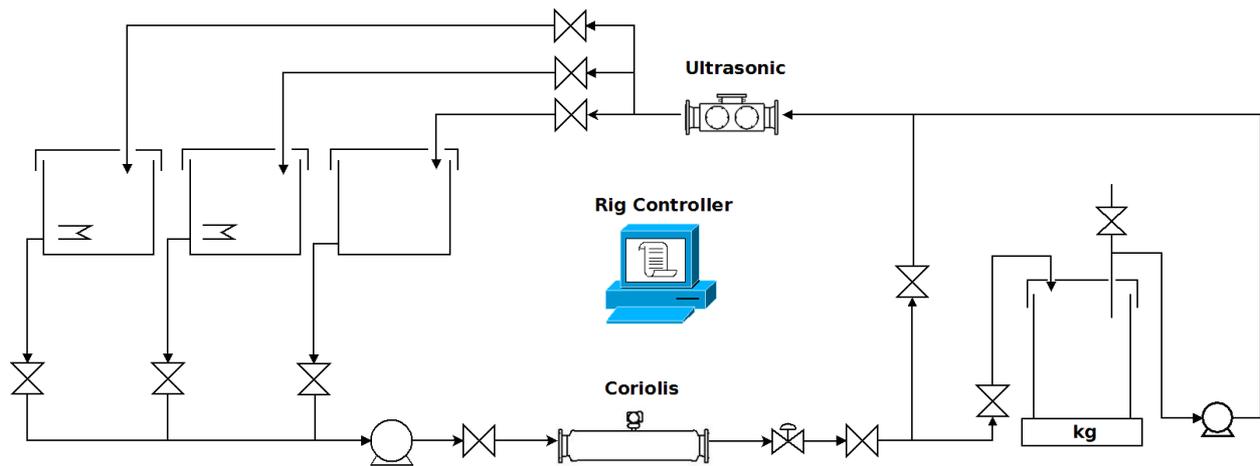


Figure 3: Calibration rig for large size straight-tube Coriolis flowmeters

To the end of the calibration procedure when all calibration factors as described in Equation (1) are determined, a linearity test is performed to make sure flow and density errors are within the specified error limits. A certificate is also produced for the user's record and all calibration data are stored electronically in the manufacturer's database. Test data at elevated temperatures are also necessary since zero stability can also be proved according to specification.

4. Extensive Test Programme and Results

In order to test large size straight-tube Coriolis flowmeters for high flow rate measurement, a test programme using various fluids and flow rigs on a DN250 Coriolis flowmeter is shown in Table 1. It includes five different fluids and five different test references over four different locations.

After the calibration of a typical DN250 flowmeter was completed, it was tested with reference to a five-beam ultrasonic flowmeter as shown in Figure 3. This ultrasonic meter is based on the transit-time measuring principle (KROHNE ALTOSONIC V), which has been approved for custody transfer applications. It is from the same manufacturer as the Coriolis flowmeter being tested, but calibrated differently in a volumetric water flow rig in the Netherlands. Five parallel ultrasonic beams can measure the flow velocities independently in the measuring tube. A computer determines the flow profile based on measured individual velocities, and uses special algorithms to correct the flow profile effect so that the volumetric accuracy can meet the custody transfer limit. The ultrasonic flowmeter has an internal temperature sensor to sense the fluid temperature, and the effect of temperature is also corrected. With a defined density value, the

ultrasonic flowmeter can output mass flow measurement. In this test programme, the reference density of water in terms of temperature is used, and the totalizer is set to mass.

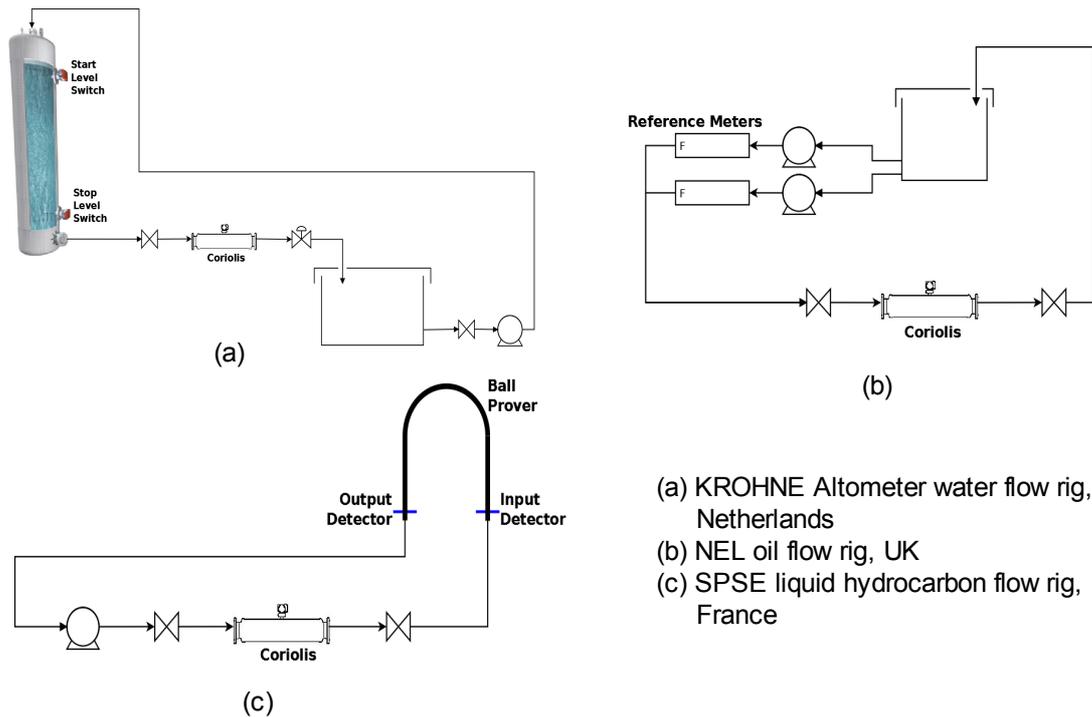
Table 1: An extensive test programme

Test Fluid			Test Reference	Test Procedure	Flow Rig
Name	Nominal density at 15°C (kg/m ³)	Nominal viscosity at 20°C (mm ² /s)			
Water	999	1	Weigh scale	Standing start and stop	KROHNE Ltd., UK
			Five-beam ultrasonic flowmeter		
			Volumetric water tower+reference density		
Kerosene	796	2.3	Turbine flowmeter	Flying start and stop	NEL, UK
Naphtha	745	0.9	Prover loop+reference density		SPSE, France
Arabian oil	891	27			
Dalia oil	908	73			

The reference ultrasonic flowmeter is at the downstream to the Coriolis flowmeter in the circulation line. Immediately upstream to the ultrasonic flowmeter inlet, a 10D straight section with a flow straightener is installed. In addition, a 5D outlet straight section is also used for the ultrasonic flowmeter. When flow reaches a relatively steady state, the rig computer simultaneously sends a trigger to both the ultrasonic and Coriolis flowmeters through the modbus communication to reset the (mass) totalizers to zero. After about four minutes, the totalizers are read simultaneously by the rig computer. The difference between them is then recorded and reported.

Following the test in comparison with the ultrasonic meter, the same DN250 Coriolis flowmeter was installed in another water flow rig in Netherlands. It was aimed to test the meter with a volumetric reference rather than a gravimetric reference in its original calibration rig. This flow rig is schematically shown in Figure 4(a), where the primary reference is a water tower. This water tower has a capacity of almost half million litres with a height of about 45 meters. Within this tower, there are a number of level switches. Since the height between level switches is known, a volumetric reference can be well defined. Flow is generated by gravity and regulated by a downstream control valve. As temperature is also monitored and water density can be determined accordingly, a reference mass can be readily calculated.

Test runs at five different flow rates were performed and each flow rate was repeated for at least three times. In a test run, immediately after water level reached the first level switch, a pulse counter started counting by receiving mass pulses from the Coriolis flowmeter. Another level switch then set a stop condition for the pulse counter. These two level switches define a flying start and stop procedure, where the total reference volume is about 22m³.



(a) KROHNE Altometer water flow rig, Netherlands
 (b) NEL oil flow rig, UK
 (c) SPSE liquid hydrocarbon flow rig, France

Figure 4: Various flow rigs used in the test programme

One of the major applications for large size Coriolis flowmeters is the oil and gas industry. Tests in two external oil flow rigs as described in Table 1 are specifically aimed to address these applications.

NEL oil flow rig is schematically shown in Figure 4(b), where two turbine flowmeters provides the reference. These reference flowmeters are calibrated against a weigh tank prior to the test runs. Depending on the test flow rate, these two reference flowmeters can be used singly or together. The test fluid was Kerosene with nominal density and viscosity values shown in Table 1. Similarly to other tests, repeated runs at five different flow rates were tested. Between flying start and stop, pulses were counted for two minutes from both the test meter and the reference meters. Temperature and pressure were also taken into account to calculate the reference mass.

The same DN250 flowmeter was also tested in the SPSE (Société du Pipeline Sud Européen) liquid hydrocarbon calibration laboratory in France. This flow rig is schematically shown in Figure 4(c), where a ball prover provides the reference. This ball prover has a standard volume of 15m³. Three hydrocarbon liquids were available in the laboratory to cover a wide range of densities and viscosities. With density accurately measured by a density meter, the reference volume was converted to a reference mass so as to compare with the Coriolis flowmeter.

The overall test results conducted in various rigs using different fluids and testing procedures are summarised in Figure 5. Data points on the graph represents the average error of repeated runs at a certain flow rate while the error bars in the graph indicates its experimental standard deviation. Together with the data points, 0.2% limits according to OIML R 117-1 Accuracy Class 0.3 are also shown as upper and lower boundaries for comparison. It is interesting to note that the general trend of errors is within the custody transfer limit despite various references were used.

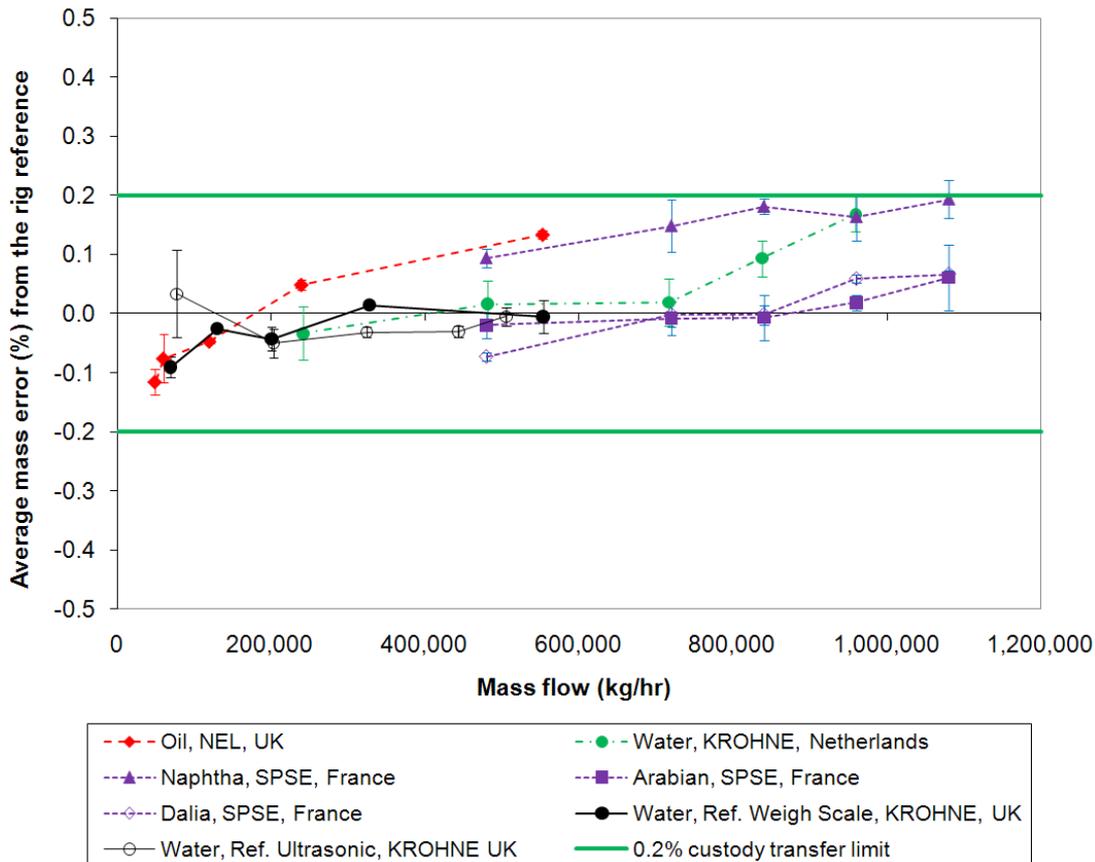


Figure 5: Summary of test results

5. Conclusions

Review of available Coriolis flowmeters seems to suggest that mass flow rate for water under 1bar pressure drop can be used to classify their flow measuring range. 1000t/hr appears to be a threshold point to define the high flow range. Research and development using a twin straight-tube configuration to extend flow measurement capacity to the high flow range above 1000t/hr is reported in this paper. A comprehensive equation for mass flow rate measurement is proposed and its importance to guide the flow sensor design and calibration is also described.

An extensive test programme on a typical DN250 straight-tube flowmeter is reported. The test programme covered five different fluids and five different test references over four different locations. Test results were within the well accepted custody transfer limit and verified the performance of straight-tube Coriolis flowmeters for flow measurement in the high flow range. Together with the existing bent-tube technology, this represents an important step forward to extend flow measurement capacity .

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Notation

u	transverse deflection	ν	tube Poisson's ratio
θ	rotation	G	tube shear modulus
x	position at a specific point along the measuring tube	k	tube shear correction factor
t	time	δ	a constant: $\delta=1$ if axial motion is constrained (e.g. a clamped-clamped end condition), or $\delta=0$ if not constrained
v_0	flow velocity	\dot{m}	mass flow rate
A_f	tube internal area	k_R	flow calibration factor
ρ_f	fluid density	t_d	time delay between two motion sensors on the measuring tube
I_f	fluid rotary inertia	t_0	time delay during zero flow
σ_0	initial axial stress	α_m	secondary flow correction factor
\bar{p}	mean internal pressure	β_m	non-linear flow correction factor
ρ_p	tube density		
A_p	tube cross-sectional area		
I_p	tube rotary inertia		
E	tube Young's modulus		