Main Menu

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Technical Paper

# Performance Testing of Novel Fibre Optic Based Vortex Flow Meter In High Pressure Wet Steam

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## 1 ABSTRACT

TNO has developed a fibre optic based vortex meter specifically aimed at high-temperature steam applications. This development was sponsored by Shell and a commercial version of the meter will be sold as “SmartFlow” by Smart Fibres Ltd, a UK company specializing in fibre optic sensors.

Besides being able to measure volume flow rate in a (near)-single phase flow, the meter was specifically designed to give an indication of the amount of liquid present in a two phase flow. This was verified in both low-pressure air-water flow loop tests and in high pressure, high temperature, wet steam tests.

This flow meter yields two benefits over conventional vortex meters. Firstly, the ability to provide an independent measurement of steam quality - the mass fraction of steam in the vapour phase. Secondly, this steam quality measurement can be used to correct the over reading, commonly observed in conventional vortex meters when used in wet steam flows. Applying the correction results in much more accurate wet steam flow measurements.

## 2 INTRODUCTION

In heavy oil production steam-based recovery methods are increasingly used, mainly due to the smaller environmental impact and the ability to reach deeper accumulations compared to open-pit mining. In order to ensure optimum heating, the steam flow rate and the steam quality (the fraction of steam in vapour phase) injected into the wells need to be monitored and controlled. However, at the moment there are no adequate and cost-effective metering solutions available for permanent steam flow and steam quality monitoring.

TNO has developed a fibre optic based Vortex Shedding flow meter, which is specifically designed to also estimate the amount of liquid present in a two phase flow. This property of the flow meter makes it very suitable for use in steam-based oil recovery applications. This paper describes wet-gas tests performed on Shell’s multi-phase flow loop (DONAU) with low-pressure air and water, and tests performed at AREVA’s High Pressure High Temperature test facility (BENSON), a specialised steam test facility of which there are only a few available world-wide.

The goal of these tests was to confirm the ability of the flow meter to accurately measure gas (volume) flow in wet-gas and wet-steam conditions.

## 3 FIBRE OPTIC VORTEX FLOW METER

### 3.1. Main drivers

The main drivers for Shell sponsoring this flow meter development were the following:

- Availability of a cost-effective solution for permanent monitoring of the rate and the quality of the steam injected into steam injection wells.
- Making use of the specific advantages of fibre optic sensing:
    - No local electronics, making the meter extremely suitable for high-temperature environments and hazardous zones (zone 0,1 and 2);
    - Multi-drop, possible to read 10-20 flow meters with one single fiber;
    - No EM interference.

At the start of the project the target specifications of the flow meter shown in Table 1 were defined for steam velocity (volume flow) and steam quality predictions.

**Table 1: Target specifications**

| Parameter | Value |
|---|---|
| Steam velocity [m/s] | 2 - 20 ± 3% (of reading) |
| Steam quality [%] (vapour mass fraction) | 40 - 100 ± 20% (absolute) |

### 3.2 Sensor design

The sensor developed for the steam flow meter has a triangular vortex bluff body with a downstream vane (Figure 1). The latter attribute differs from a conventional vortex meter, which typically uses piezo-based electronics to measure forces on a bluff body positioned in a pipe.

In the proposed steam flow meter, the conventional force sensors are replaced by a fibre optic pick-up (Fibre Bragg Grating, FBG) embedded inside the downstream vane. FBGs, consist of an optical fibre imprinted with a grating pattern in the core of the fibre. When light of a broad-wavelength spectrum is fed into the fibre, the grating reflects only light of a wavelength which corresponds to the spacing of the grating. Elongation or compression of the grating, caused by the induced micro-motion of the vane due to vortex shedding, will change the spacing of the grating and hence the wavelength of the back reflected light at FBG. This allows the fibre to act as a local strain gauge, measuring the dynamic loads imposed on the vane by the vortex shedding.

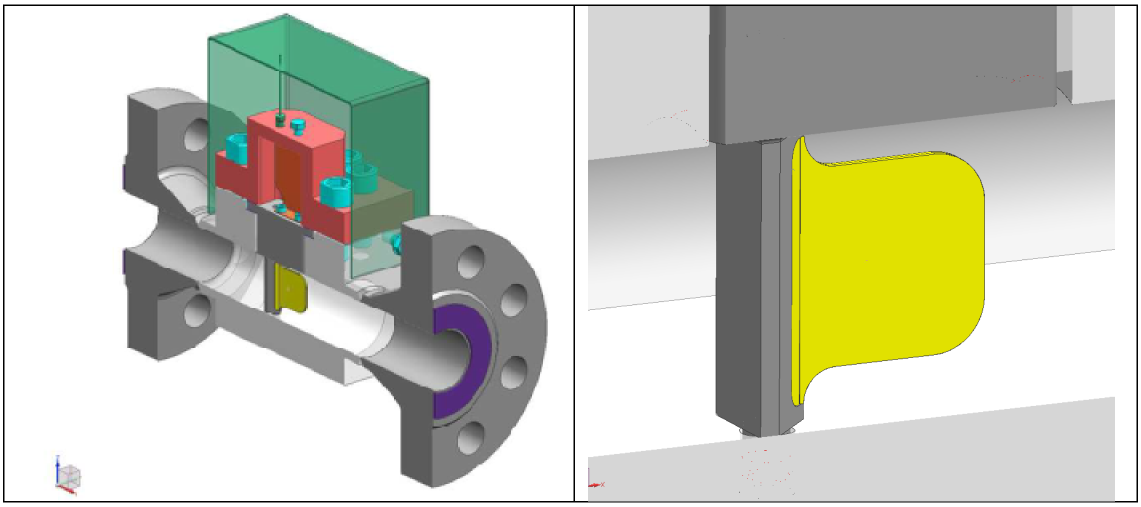

**Figure 1: Mechanical layout of the SmartFlow. Note that in the current figure, the orientation off the bluff body and vane is vertical whereas the orientation in all two phase tests was horizontal.**

A more detailed description of the meter is given in [1].

### 3.2 Performance in two phase flow

Vortex flow meters are normally used for single phase flow. Generally, vortex flow meters are not used in two-phase flow metering mainly because of the high over-reading inherent to these flow conditions. However, the proposed fibre optic flow meter has overcome these limitation as will be demonstrated below.

Assuming that the flow meter is use in a horizontal steam flowline, the vortex shedder bar of the fibre optic flow meter is mounted horizontally to avoid interference between the liquid film and the shedder bar. To mitigate high liquid holdups or slug flow at lower flow rates it is advised to place the meter in a slight downslope.

The vane of the shedder bar is used to pick up the vortex shedding frequency caused by the bluff body. The vortex shedding frequency is proportional to the local velocity:

$$f = \frac{Sr}{D_{body}} U \tag{1}$$

In addition, the vane is also used to determine the gas quality of the two phase flow. The gas quality, or steam quality in case of a (two phase) steam flow saturated steam vapour ($m_{ss}$) and water ($m_w$) can be expressed using:

$$\lambda = \frac{m_{ss}}{m_w + m_{ss}} \tag{2}$$

This unique feature has been achieved in two different but complementary ways:

1. using the interaction with the vane of the shedder bar and the liquid layer flowing at the wall/bottom of the flow meter. The shape of the vortex peak can be used to estimate the amount of liquid, and is described by a dimensionless value named *'Vortex Peak Quality factor'* ($Q_{vp}$).
2. using the interaction with the vane of the shedder bar and the mist flow. The amount of interaction can be determined by the relative change in mechanical *eigenfrequency* of the vane.

In Figure 2 an example is shown of the spectogram obtained with the vane attached to the shedder bar when taking a sample for 60 seconds. In this case the vortex-shedding peak is observed at $f_v$ = 196 Hz and the mechanical peak at $f_m$ = 984 Hz.

The red line and red circle show the polynomial curve fit and the fitted maximum for the mechanical peak. The pink line shows the polynomial curve fit for the vortex-shedding peak and the pink circle shows the fitted maximum for the specific peak.

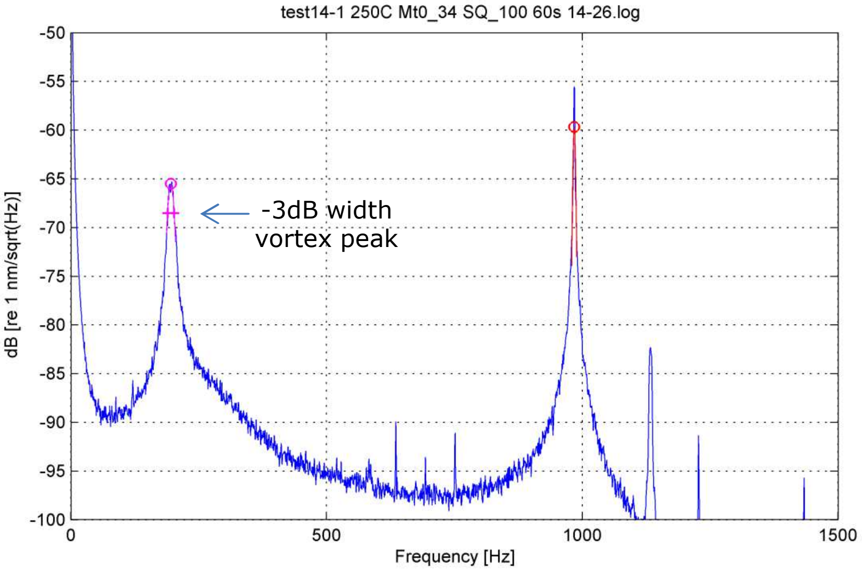

**Figure 2: Frequency spectrum of the vane attached to the shedder bar.**

The Vortex Peak Quality factor is expressed as:

$$Q_{vp} = \frac{f_v}{\Delta \mathrm{f}_{\text{-3dB}}} \tag{3}$$

In Figure 2, the pink crosses indicate the -3dB limits that are used to compute $\Delta f_{3dB}$ of the vortex-shedding peak. In this case the -3dB width of the vortex-shedding peak is 12 Hz, and the vortex-shedding peak is at at $f_v$ = 196 Hz, resulting in a Vortex Peak Quality factor ($Q_{vp}$) of 16.3.

To evaluate the actual upstream superficial velocity and the gas quality, the following procedure can be applied:

- First, determine the characteristics of the vortex shedding:
  - Vortex peak frequency
  - Vortex Peak Quality factor ($Q_{vp}$)

- Then estimate the velocity assuming single phase flow:

$$U_{sg,dry} = \left(\frac{fD}{Sr}\right)\left(\frac{A_{tube} - A_{body}}{A_{tube}}\right) \tag{4}$$

  With $A_{tube}$ the tube area [m$^2$] and $A_{body}$ the blockage area of the meter [m$^2$], $f$ the vortex shedding peak frequency [Hz], $D$ the diameter of the shedder bar [m] and $Sr$ the Strouhal number of the actual velocity at the vortex meter [-].

- Then determine the gas quality of the two phase flow by using the fit function of the Vortex Peak Quality factor ($Q_{vp}$) or by making use of the fit function of the shift in mechanical eigenfrequency. The steam test results presented in this paper only uses the fit function of the Vortex Peak Quality factor ($Q_{vp}$).

- Then evaluate the liquid correction factor based on a simplified model between the gas quality ($\lambda$) and the liquid hold-up ($\alpha l$).

- Followed by a second estimate of velocity assuming two phase flow conditions:

$$U_{sg,wet} = \left(\frac{fD}{Sr}\right)\left(\frac{A_{tube} - A_{body} - A_{liq}}{A_{tube}}\right) \tag{5}$$

  with $A_{liquid}$ the liquid area ($\alpha_l$*$A_{tube}$) [m$^2$].

## 4 TESTS IN LOW PRESSURE DRY-AIR AND AIR-WATER MIXTURES

### 4.1 LP test facility

Initial trials were performed at the multi-phase flow loop (DONAU) at Shell, Rijswijk, The Netherlands. These trials were performed in dry-air and air-water at low pressure (wet gas) conditions.

Note that in Figure 3 below the orientation of the bluff body and vane is vertical, as shown in Figure 1, while for all the flow results in two-phase flow the orientation of the bluff body and vane is horizontal.

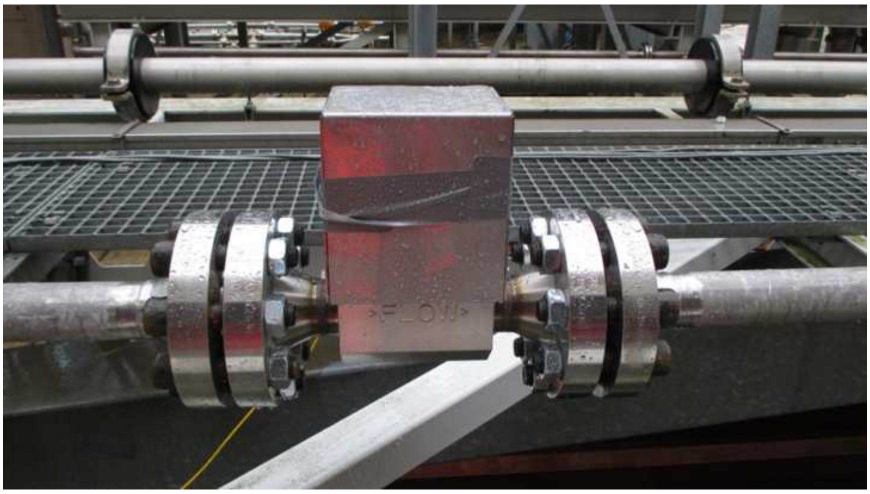

**Figure 3: Picture of the Fibre optic Vortex Flow meter in the DONAU test loop of Shell. The fibre optic cable is the yellow cable shown left of the meter.**

### 4.2 Performance in single phase dry-air

At the low pressure multi-phase test facility of Shell, the flow meter was tested over a range of single phase air velocities; from 5m/s to 27m/s.

Since the vane of the shedder bar inside the test-meter was designed for use at high line pressures the flow meter was restricted to gas velocities of 5m/s and higher, maintaining sufficient signal strength at the low pressure conditions under which the experiments were conducted (5 bara).

Figure 4 presents the results obtained in dry-air flow experiments. The results show that the deviations remain well within ±3% against the reference meter. This performance is expected of a vortex shedding flow meter in single phase flow.

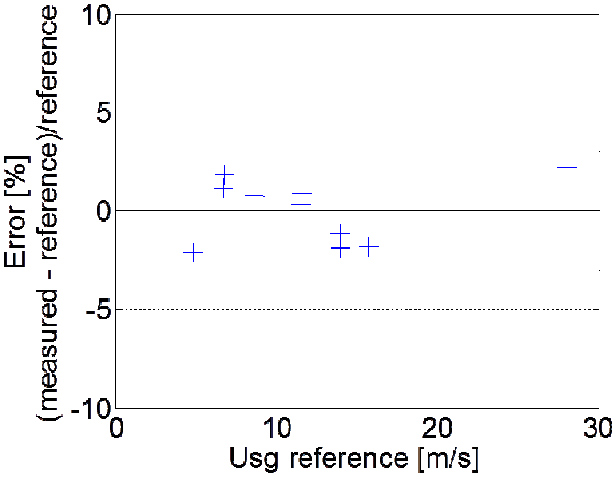

**Figure 4: Low pressure (5 bara) results of single phase conditions.**

### 4.3 Performance in two-phase air-water

In Figure 5 the results are shown obtained from the low pressure flow experiments in two-phase flow (air and water mixtures). It clearly shows that without correction over-readings in the measured flow velocity may occur of up to 40% at increasing liquid holdup (see colour bar in Fig.5). The figure also demonstrates that as long as the holdup remains below 5% the measurement error remains within ±5%.

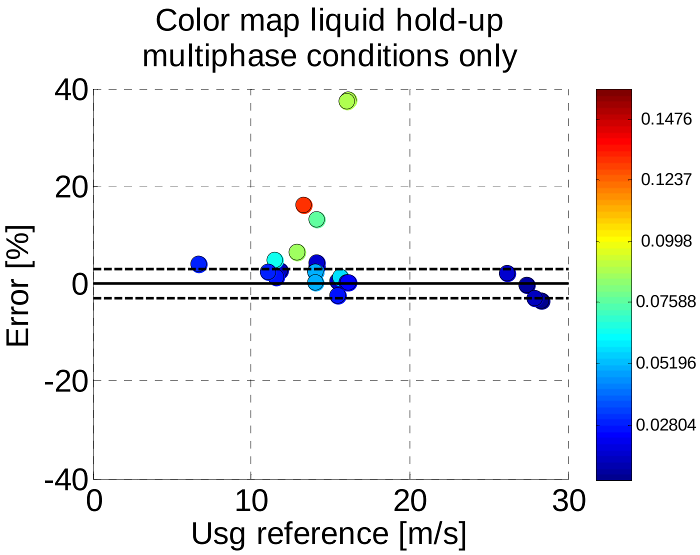

**Figure 5: Low pressure (5 bara) results of two phase conditions. The colors indicate the liquid hold-up based on OLGA (an industry standard dynamic multiphase simulator) simulations.**

Figure 6 and Figure 7 show the relationship between liquid hold-up and gas quality as a function of the Vortex Peak Quality factor ($Q_{vp}$) and the mechanical eigenfrequency. Both figures show a clear relationship between the liquid content in the two-phase flow mixture and the response of the vane.

The change in the peak-quality is presumably caused by interference between the liquid distribution around the shedder bar (i.e. stratified film and waves at the wall/bottom of the flow line) affecting the uniformity of the velocity profile around the shedder bar, leading to a broader frequency peak.

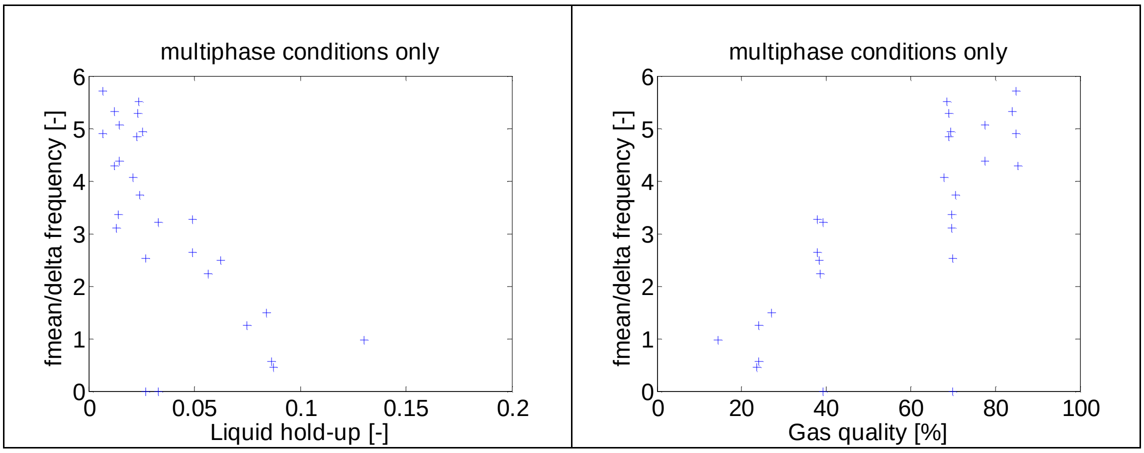

**Figure 6: Relation Vortex Peak Quality factor ($Q_{vp}$) as function of liquid hold-up and gas quality.**

On the other hand, the eigenfrequency of the vane is known to be affected by the added mass of the medium surrounding the vane. For example, as more droplets are entrained in the gas flow, the eigenfrequency is reduced.

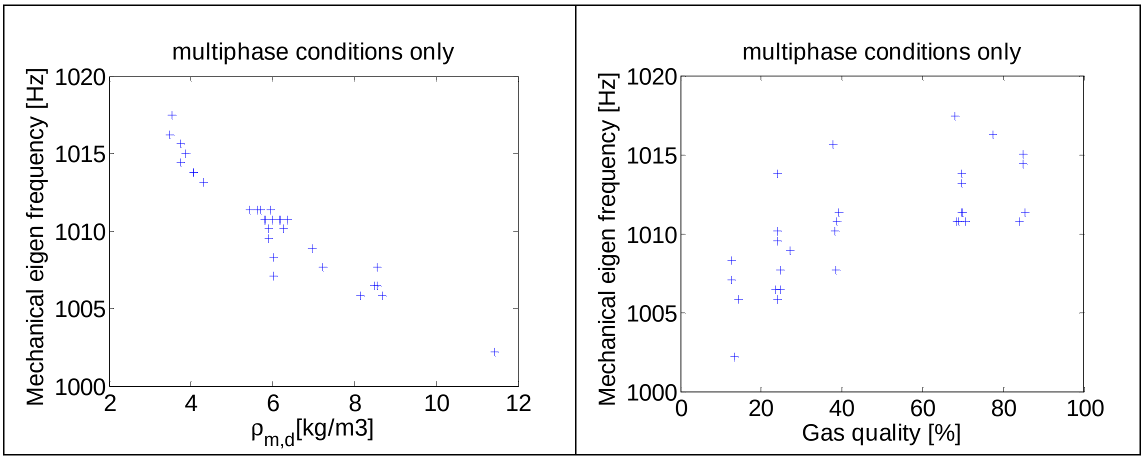

**Figure 7: Relation mechanical eigenfrequency with the mixture density (droplets + gas) and with the gas quality.**

## 5 TESTS IN HPHT STEAM

### 5.1 HPHT steam test facility

An extensive test program was carried out at the High Pressure High Temperature (HPHT) steam test facility (BENSON) of AREVA, Germany, in November and December 2013. At this unique test facility, steam velocities, qualities and line-pressures can be accurately controlled within a wide operating range given in Table 2.

The steam quality was determined from the heater input. This requires knowing the heat loss along the insulated loop, which was determined from calibration runs prior to the test period. The uncertainty of the reference steam quality was +/- 2.8% absolute.

The uncertainty of the reference steam mass flow was +/- 1.3% of the actual reading.

The vortex meter was placed in a slightly downward slope (-1 °). The flow meter and shedder bar were mounted in a horizontal position as indicated in Figure 8.

**Table 2: Test conditions**

| Parameter | Value |
|---|---|
| Steam velocity [m/s] | 1 – 14 |
| Steam quality [%] | 40 – 100 |
| Pressure [bara] | Up to 140 |
| Temperature [°C] | Up to 355 |
| Inclination [°] | -1 |
| Pipe ID [mm] | 47.7 |

The flow meter was connected to a patch cord composed of 2m of PEEK tubing followed by 48m of simplex cable. The patch cord ran up to the control room to be connected to the fibre optic read-out unit, called SmartScan (shown right, the small blue box in right-hand photograph in figure 8) which outputs the data to a lap-top.

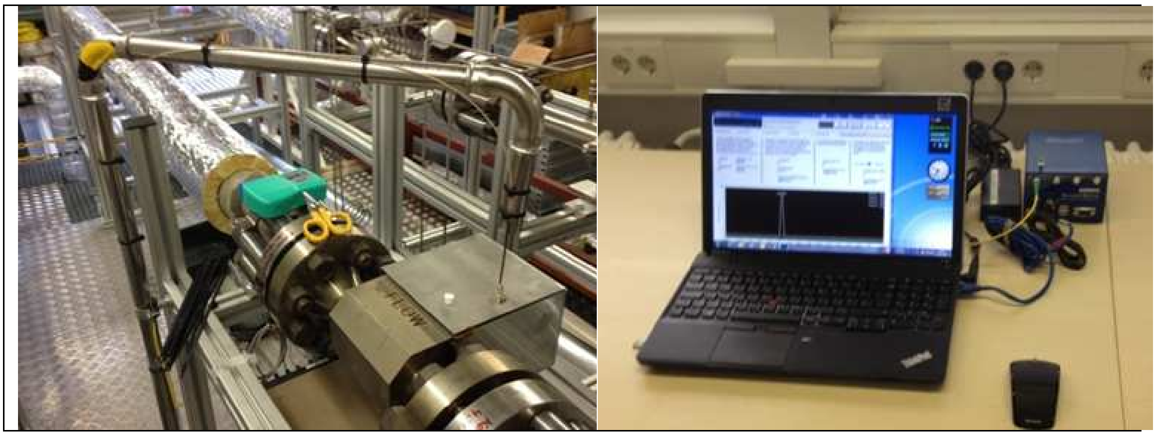

**Figure 8: Photos of the fibre optic flow meter installed in the AREVA Benson test loop.**

## 5.2 Performance in dry steam

The test results in dry steam are shown in Figure 9 for the line-pressures applied during the flow trial; 40, 80 and 120 bar. Figure 9 shows that the deviation against the reference meter is less than ±3% for all flow velocities above 6 m/s. Overall the measurement error remained within ±5%.

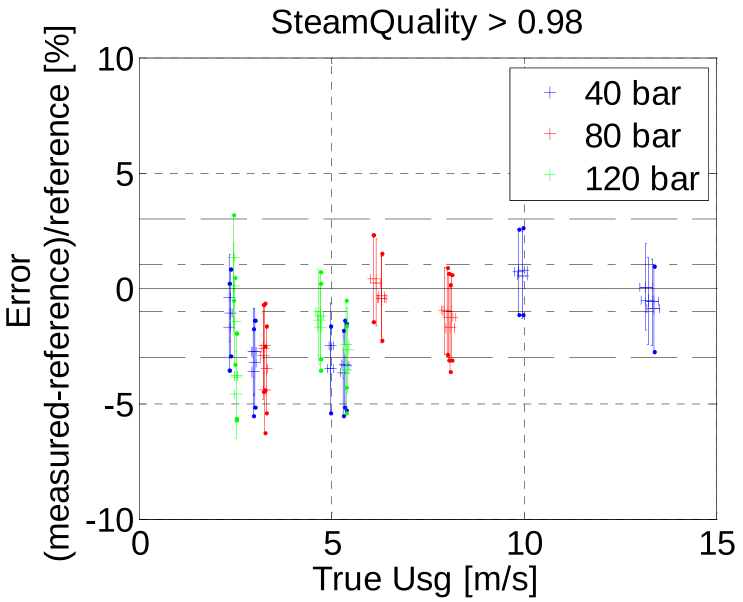

**Figure 9: Measurement result dry steam (SteamQuality > 0.98) as function of reference velocity. Uncertainty reference meter ±1.25%.**

## 5.2 Performance in Wet Steam

### 5.2.1 Steam quality prediction

In paragraph 3.2, two parameters were identified which could be used for determining the steam quality; the Vortex Peak Quality factor and the mechanical eigenfrequency of the sensing assembly (shedder bar and vane).

It has been shown that the mechanical eigenfrequency clearly relates to the fluid density in pressurised gas flows, which make this parameter a suitable candidate to be considered for mixture-density measurements and hence steam quality measurements in highly entrained steam flows, like mist flows.

All flow conditions in the BENSON flow loop were also simulated with OLGA. Note that for all steam flow tests the entrainment (the fraction liquid droplet in the steam) were predicted to stay below 50% as shown in Figure 10. This means that in all cases the liquid was predominantly flowing at the wall/bottom of the flow meter in a rivulet as is illustrated in Figure 11 (stratified flow).

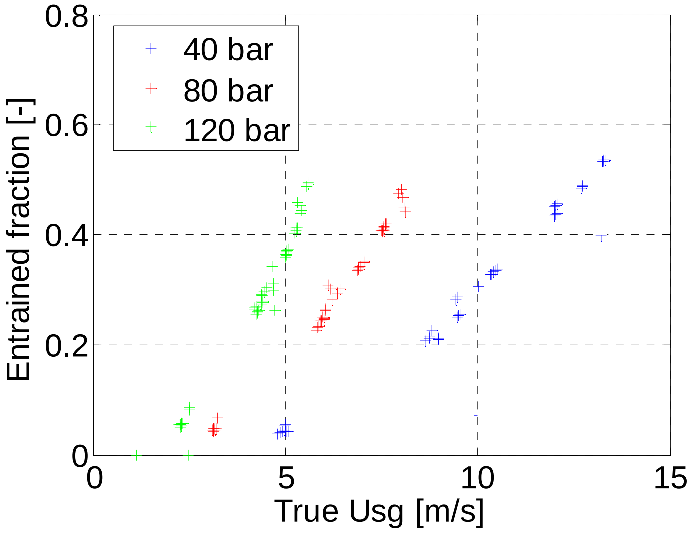

**Figure 10: Entrainment rates for all Areva tests. The maximum entrainment rate is 50%.**

**Figure 11: Illustration of the blocking effect of water hold-up on the actual velocity perceived by the meter.**

The correlation between the liquid holdup and the quality of the steam versus the Vortex Peak Quality factor is illustrated in Figure 12.

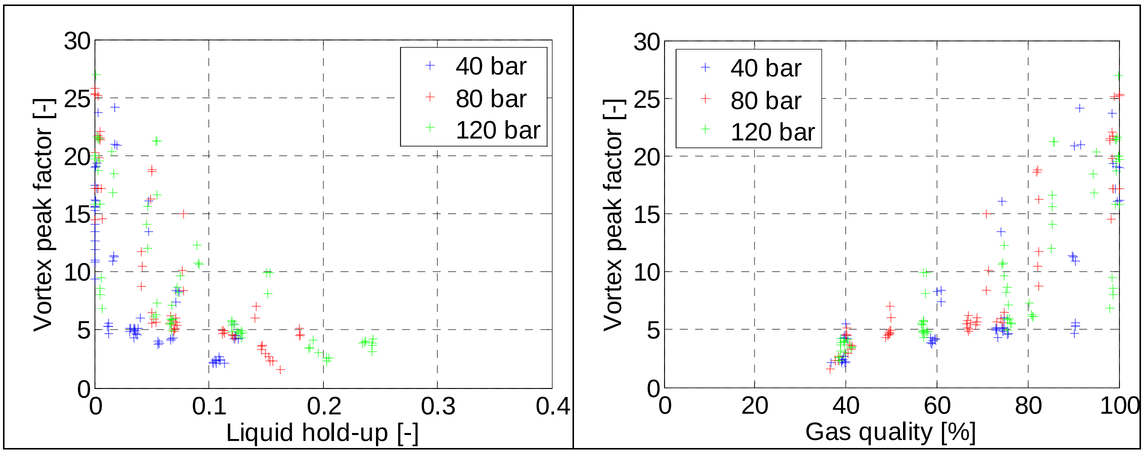

**Figure 12: Relation Vortex Peak Quality factor as function of liquid (condensed steam) hold-up and steam quality.**

The results may be rewritten, taking into account the flow quality, best displayed against the steam quality (Figure 13), showing a clear correlation between the reference steam quality and Qvp*Usg derived from the measured data (called $SQ_{meas}$). Note that correlation holds in wet-steam but gets undefined at dry-steam conditions (dots in the red circle).

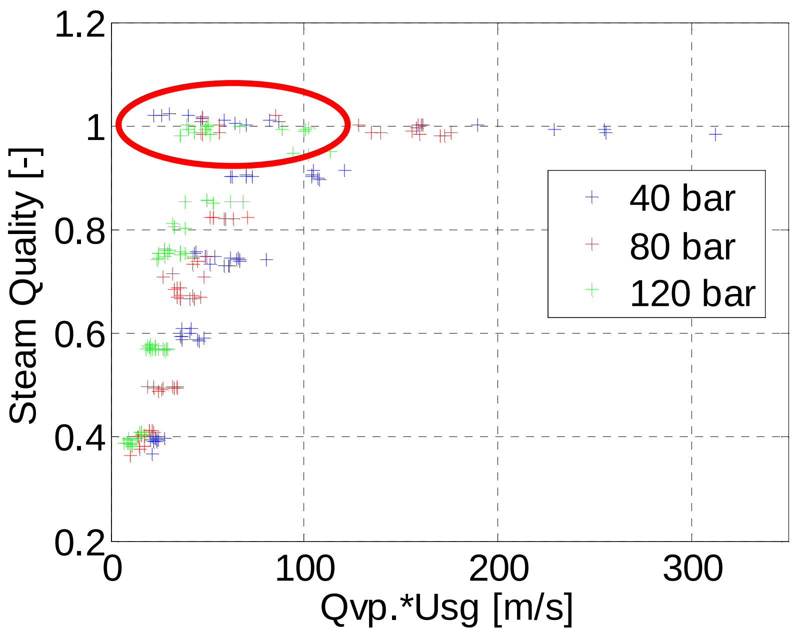

**Figure 13: Steam quality as function of corrected Vortex Peak Quality factor ($Q_{vp}$).**

Figure 14 shows a cross-plot of the estimated steam quality ($SQ_{meas}$) with the reference (actual) steam quality for all test conditions including flow velocities below 7m/s, showing deviation exceeding ±20% (abs).

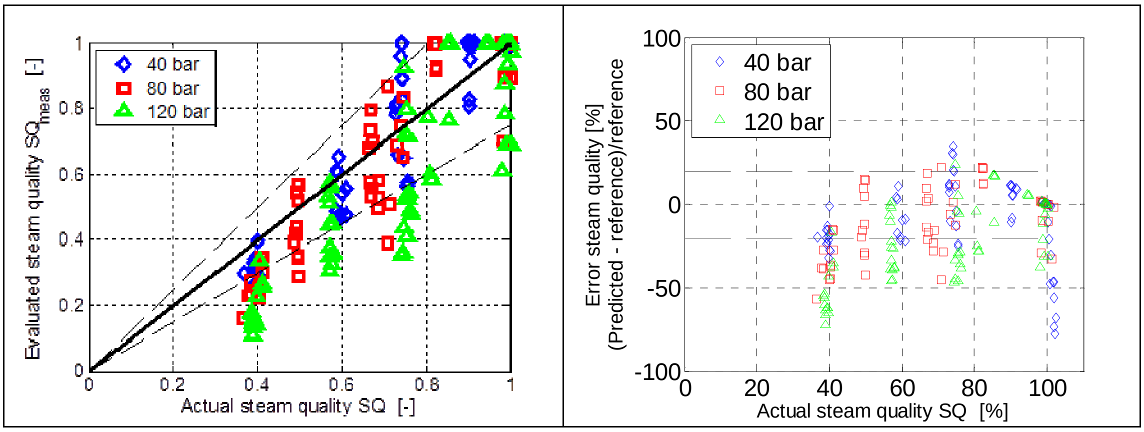

**Figure 14: Estimated compared to actual steam quality for all evaluated test conditions.**

Figure 15 shows the same comparison for all test data at flow velocities above 7m/s. It is clear that higher flow velocities work in favour of $SQ_{meas}$, reducing the deviations to within ±20% (absolute). Note that in the field the flow velocities are expected to be around 10 m/s (and 15 m/s as the upper range).

The results shown in Figure 15 are solely based on tests done at the lower line pressures (40 and 80 bar). At 120 bar the flow velocities remained well below 7m/s due to test loop limitations.

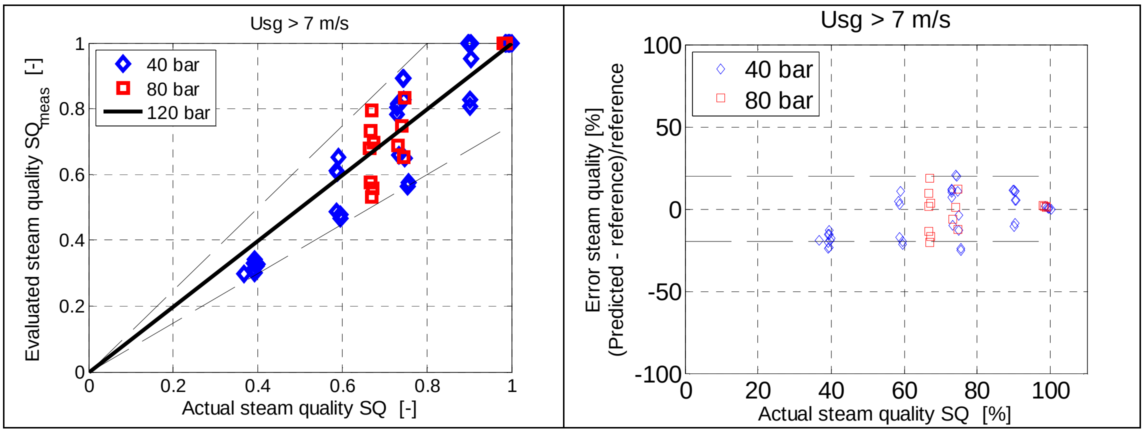

**Figure 15: Estimated compared to actual steam quality when Usg> 7 m/s. Dashed lines give +/- 20% error.**

The observation that the correlation works better at higher velocities is most likely caused by the fact that the holdup varies much more at low velocities and that at these conditions the hold-up is generally much higher.

### 5.2.2 Correction velocity over-reading in wet steam

In the case of wet-steam the flow velocity was calculated directly from the observed vortex frequency, as indicated in equation (1), the over-reading of the can be as high as 60% compared to the reference data (Figure 16). Again, at higher velocities (Usg > 7 m/s) the error reduces down to 40% due to a lower holdup.

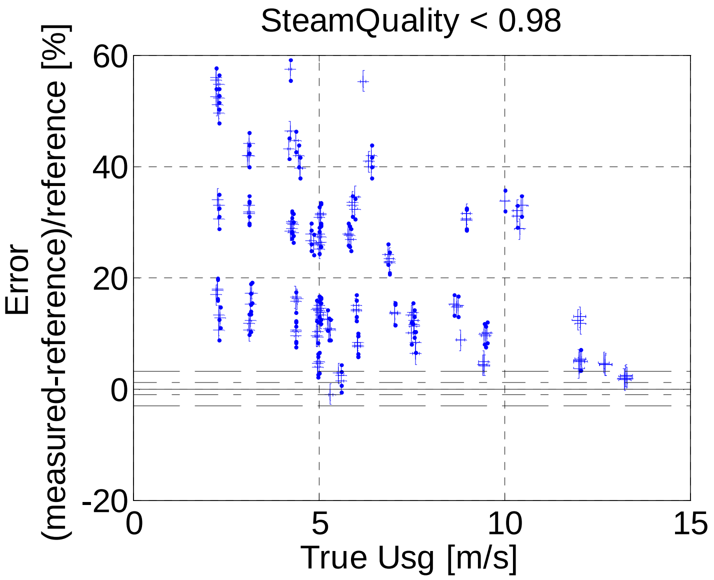

**Figure 16: Error as function of reference superficial gas velocity uncorrected for the wetness. Dashed lines indicate ±1 and ±3% lines.**

Based on OLGA simulations it was found that at higher velocities, the liquid holdup was primarily dependent on the steam quality. Based on this knowledge correlations were developed to correct for holdup resulting in a much reduced over-reading and errors typically less 10% (Figure 17).

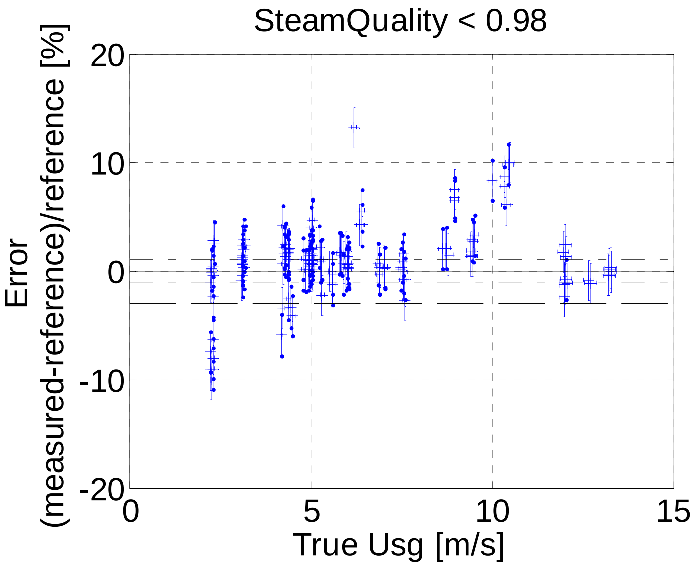

**Figure 17: Error as function of reference superficial gas velocity. In this plot the actual Superficial velocity is corrected using simple hold-up prediction model and the steam quality set in the AREVA Benson test loop. Dashed lines indicate ±1 and ±3% lines.**

Note that this approach and holdup correction can be applied for (conventional) vortex meters when the actual steam quality is known or can be estimated as with the proposed flow meter using the method outlined above.

Results for the whole dataset are presented in Figure 18. The deviations are less than +/- 10% for all flow velocities higher than 7 m/s whereas compared to Figure 16 (no hold-up correction) the errors are in the order of +40%.

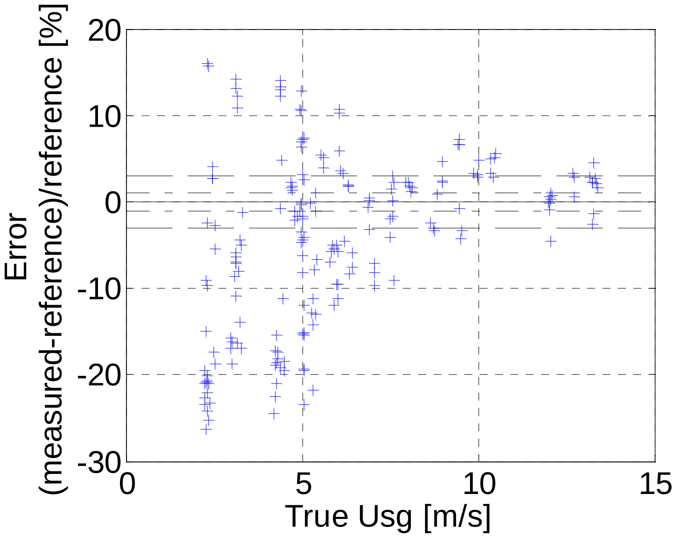

**Figure 18: Error as function of reference superficial gas velocity. In this plot the actual Superficial velocity is corrected using the simplified hold-up model and the steam quality derived from the Vortex Peak Quality factor determined by the meter. Dashed lines indicate ±1 and ±3% lines.**

## 6 CONCLUSIONS

This paper introduces a novel fibre optic vortex meter (SmartFlow) and describes its performance and test results in two phase flow at both low pressure (air-water) and high pressure, high temperature conditions (wet steam).

This flow meter yields two benefits over conventional vortex meters. Firstly, the ability to provide an independent measurement of the quality of a wet gas or steam flow. Secondly, this flow quality measurement can be used to correct the over-reading commonly observed in many flow meters when used in wet gas flows, resulting in much more accurate flow measurements.

The flow meter uses a shedder bar with a vane in which a fibre optic strain sensor is attached. This fibre optic strain sensors measures the vortex shedding frequency and the mechanical eigenfrequency of the vane.

The flow meter provides measurements of the actual gas velocity and the gas quality. The latter measurement is a unique feature of this flow meter and is not possible using a conventional vortex meter.

The mechanical eigenfrequency shifts with the effective density of the surrounding fluid around the sensing element of the flow meter and can therefore be used to determine the droplet concentration which is related to flow quality. Therefore, this parameter is most useful at conditions where the entrainment rate is high (> 50%), for which we have found evidence at high velocities, in the air-water experiments.

The second parameter that can be derived from the sensing element is the quality factor of the vortex shedding peak. The quality factor is the width of the peak compared to the central frequency. It was shown that an estimate of the gas quality can be made at low entrainment rates (< 50%). In wet steam flow, this was successful at velocities exceeding 7 m/s.

The HPHT steam tests that were performed demonstrated the following:

- At high steam qualities (above 98% which is ‘dry’ steam) errors in steam flow measurements are less than 3% for velocities above 7 m/s; between 2 and 7 m/s errors are less than 5%.
- At lower steam qualities the errors in steam mass flow measurement increased to 60%, similar to conventional vortex meters. This effect is due to the liquid holdup and (shedder bar) meter blockage which increase the local vapour velocity
- The steam tests confirmed the ability of the flow meter to give an estimate of steam quality with errors within 20% absolute. Steam quality was estimated by making use of the Vortex Peak Quality factor only since high entrainment (> 50%) could not be reached in the test loop. At higher entrainment rates (and thus velocities than could be tested in this loop), the mechanical eigenfrequency may provide an independent measure of steam quality as demonstrated in the low pressure air-water tests.

The availability of the steam quality measurement allows further corrections to the velocity and mass flow measurement. The liquid holdup can be estimated from the measured steam quality and flow rate using simplified holdup models based on multiphase flow simulations using OLGA. Note that these simulations must be done in advance and must cover the range of conditions encountered by the flow meter. Making these corrections reduced the errors in steam (vapour) mass flow measurement to +/-10% for higher velocities (Usg > 7 m/s).

Following the tests described in this paper, discussions are ongoing to test SmartFlow in a Shell-operated field application. In addition, more high velocity steam trials are planned to evaluate the performance at the conditions closer to the field. Furthermore, new algorithms will be developed and tested using both the mechanical peak frequency as well as the Vortex Peak Quality factor to further improve the steam quality prediction and therefore also the steam gas velocity prediction.

## 7 ACKNOWLEDGEMENTS

The author would like to thank the people from Shell Canada (Andy Znotins, Nick Goodman and Mirko Zatka) for making this project possible and giving good steer of important requirements from an end user perspective. The author would also like to thank the Hans den Boer from the In Well Technology team Shell Rijswijk involved in the development from the start and his coordinating role within the project to test the performance of other meters as well during the wet steam test campaign.

## 8 ANNOTATION

| | |
|---|---|
| $A_{tube}$ | crossectional tube area [$m^2$] |
| $A_{body}$ | crossectional area shedder bar (D*ID) [$m^2$] |
| $A_{liquid}$ | cross sectional area liquid ($\alpha l * A_{tube}$) [$m^2$] |
| D | shedder bar diameter [m] |
| ID | tube diameter [m] |
| $m_{ss}$ | Mass saturated steam |
| $m_w$ | Mass water (condensed steam) |
| Sr | Strouhal number (based on actual fluid velocity at shedder bar [-] |
| $U_{sg}$ | superfical gas velocity upstream SmartFlow [m/s] |
| $U_{sg,dry}$ | superfical gas velocity upstream of SmartFlow meter (assuming dry gas) [m/s] |
| $U_{sg\_wet}$ | superfical gas velocity upstream of SmartFlow meter (assuming wet gas) [m/s] |
| $Q_{vp}$ | Vortex Peak Quality factor (peak frequency/width peak at -3dB) [-] |
| SQ | steam quality [-] |
| f | vortex shedding frequency [Hz] |
| $\alpha l$ | liquid hold-up [-] |
| λ | Qaulity [-] |

## 9 REFERENCES

[1] L.K. Cheng, W. Schiferli, R.A. Nieuwland, R. Jansen, “Development of a FBG vortex flow sensor for high-temperature applications”, 21st International Conference on Optical Fiber Sensors, 77536V (18 May 2011); doi: 10.1117/12.886051