

Installation effects and flow instabilities in gas metering station with multipath ultrasonic flow meters

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ABSTRACT

This paper will address the analysis carried out in order to understand and correct flow meter effects on the Gjøa gas export metering station.

The metering station consists of two parallel metering tubes, each equipped with a multipath ultrasonic flow meter with an upstream flow conditioner. The header upstream of the two metering tubes has T-bends at the end sections. Through Computational Fluid Dynamics (CFD) it will be shown that the T-bends in the upstream header can cause severe distortions of the flow profiles, and that the positioning of the flow conditioners can be essential for preventing flow instabilities. It will be demonstrated that both the pipe geometry upstream the inlet header and the geometry of the inlet header itself may affect the flow instability through the flow meters. The results will to a large extent explain the effects found in practice.

Furthermore, it will be demonstrated how errors in the meter configuration file can affect the meter performance, even in cases where flow calibration has been carried out successfully.

1 INTRODUCTION

This work was based on the mis-measurements for the Gjøa gas export, which were discovered by Engie due to difference in flow rates when switching from one flow line of the metering station to the other. A thorough description of the observations is given in the paper of P. Chan et al. [1]. The difference in the measurements of the ultrasonic meters (USM) for the two parallel lines was initially assumed caused by installation effects. The metering response to possible installation effects were investigated based on the use of computational fluid dynamics (CFD) model.

The work also included the evaluation of the effect of wrong input to configuration files of the USMs. Additionally, it was evaluated whether the mis-measurements caused by the wrong input could be corrected within fiscal requirements based on the measured path velocities from the USMs.

The CFD model and analysis of the USM response to the modelled flow profiles are presented in Chapter 2. The analysis of the effect of wrong input to the configuration files of the USMs are presented in Chapter 3.

2 CFD MODEL AND RESPONSE OF INSTALLATION EFFECTS ON USM

In this chapter the installation effects on the ultrasonic measurement system are studied. The CFD model and analysis of the USM response to the modelled flow profiles are presented.

2.1 Measurement principle

The measurement principle for the gas export at Gjøa is flow measurements from ultrasonic flow metering (USM). For Gjøa the USMs are of the type MPU 1200 ultrasonic meters from FMC, consisting of six ultrasonic transmitter pairs. These will define six acoustic paths, each with an inclination angle relative to the flow and a defined distance from the centre of the pipe.

The acoustic paths numbered 1 and 2 are at the same plane with equal distance from the centre of the pipe. Likewise for the acoustic paths numbered 3 and 4. The acoustic paths numbered 5 and 6 are on the other hand at different distances from the centre of the pipe. Figure 2.1 illustrates how the inclination angles of the acoustic paths are aligned when the pipe is seen from above.

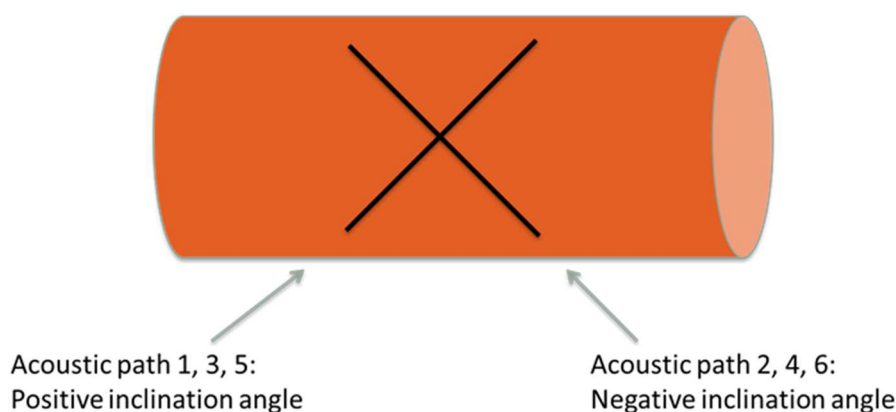


Figure 2.1 The MPU 1200 acoustic paths seen from above

The measurement principle of the USM is based on the measured six flow velocities, or path velocities, v_1 , v_2 , v_3 , v_4 , v_5 , and v_6 . To these flow velocities, there are applied six weight factors, w_1 , w_2 , w_3 , w_4 , w_5 , and w_6 . The average axial flow velocity in the pipe is calculated from the combination of these. The volume flow rate is calculated from the average axial flow velocity and the cross sectional area of the metering pipe. Additional measurements are temperature and pressure.

For the MPU 1200 flow meter, the measured flow velocities are also used to calculate four quality parameters for the flow profile. These parameters are

- Profile flatness: a quantitative description of the distribution of axial flow in the pipe. High flatness number means that the axial flow velocity in the centre of the pipe is not significantly larger than the velocity off-centre. Low flatness number indicates that the flow velocity is largest in the centre of the pipe.
- Profile symmetry: a quantitative description how symmetric the flow velocity is with respect to the centre of the pipe. If the profile symmetry is close to zero, the flow is symmetric in the pipe cross section.

- Swirl: a quantitative description of the tangential flow velocity relative to the axial flow velocity in the pipe. For swirl, the rotational flow will form one rotation cell seen in the cross section of the pipe.
- Cross flow: similar to swirl, but describes a rotational flow forming two cells seen in the cross section of the pipe.

2.2 Observations

The mis-measurements for the Gjøa gas export were discovered by Engie due to difference in flow rates when switching from one flow line of the metering station to the other. The meter shift could not be explained by operational issues, and the shift was not seen on comparison with upstream and downstream Venturi meters. The observations are presented in the paper of P. Chan et al. [1], with the conclusion that a non-ideal profile can cause a bias on the measurements and lead to significant errors of the measurements over time.

In order to clarify the reasons for the observed differences between the two flow meters, Engie initiated a study involving CFD simulations and a subsequent ultrasonic metering analysis.

During single operation of run 2, shorter time periods of increased flow rate were observed. These events are referred to as *peaks*. In addition to increased flow rate, the observations also showed flow profile changes in swirl, symmetry, and flatness values. These effects were also investigated in the CFD simulations.

2.3 CFD

The CFD code MUSIC is used in the simulations. MUSIC is an in-house finite volume code developed by CMR, and has been used in simulations of pipe flow [2].

In the simulations, equations for momentum (Navier-Stokes) and pressure are solved together with the equations for the industry standard $k-\omega$ turbulence model. With an average flow velocity of 20 m/s the Reynolds number is $4 \cdot 10^7$. Due to these high Reynolds numbers, the turbulent boundary layers at the pipe walls are very thin. The wall friction is therefore modelled with wall functions.

In the simulations, the gas is considered to be incompressible.

2.4 USM simulation

The flow profiles simulated by the CFD code are interpreted by the CMR developed program *USMSIM*, for virtual ultrasonic flow metering in CFD calculated flow profiles, used to simulate the readings from the MPU 1200 flow meter. Here the average flow velocities are calculated using the actual acoustic path location and integration weighting factors and the algorithms used in the MPU 1200 software. In this way, the effect of swirl on the flow meter volume flow rate output, is found.

2.5 Simulations and analysis

The initial objectives for the CFD analysis were:

- Investigate the effect of swirl on the volume flow reading compared to fully developed flow pattern for the gas export metering station on Gjøa. Calculate the corresponding *profile flatness* and *profile symmetry*.
- Simulation of specified flow profiles with simplification of piping configuration upstream the position of the flow meter in order to replicate these flow profiles. This part of the study was intended for an off-site calibration with replication of the observed flow profiles at Gjøa.
- Simulation of the flow pattern at the location of the USM for the given piping configuration with the existing flow conditioner at Gjøa gas export metering station. Simulation of the effect on the volume flow reading from these flow patterns compared to fully developed flow pattern.
- Simulation as listed in the previous point, with an optimised location of the flow conditioner. Investigate whether a re-location of the flow conditioner can lead to a fully developed flow profile.

The initial objectives were adjusted according to the findings of incorrect input to the configuration files of the USMs. The simulations were performed based on a configuration with correctly implemented inclination angles of the ultrasonic transducers, and thereby the results would apply to the corrected and future operation of the Gjøa metering station for export gas.

2.5.1 Simulation geometries

The simulations were based on the following geometries:

- An arbitrary two-bends-out-of-plane geometry with regular bends for the investigation of swirl effects in general for USM measurements
- Similar to the existing installation geometry, but with regular bends instead of T-bends at the header.
- Similar to the existing installation geometry of the export gas metering station,
 - o without flow conditioner
 - o with flow conditioner positioned as is
 - o with flow conditioner in a new position closer to the flow meter

The different simulation geometries are illustrated in Figure 2.2 and Figure 2.3. The distance between the flow conditioner and the flow meter is 15 D (4.465 m).

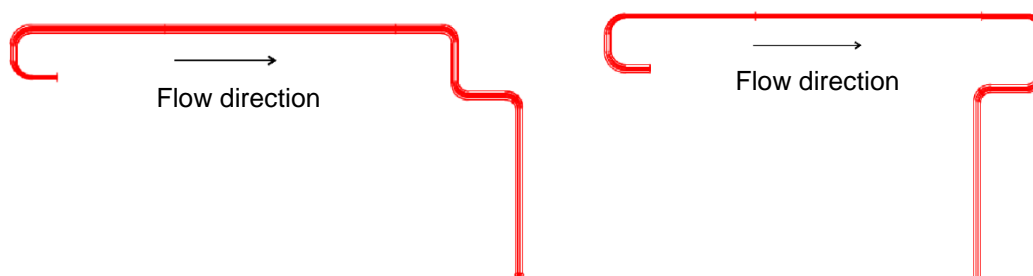


Figure 2.2 Single operation simulation geometry, simplified metering station with regular bends. The arrows indicate the direction of the flow. The upper part of the figures show the upstream piping. Left: single export run 1. Right: single export run 2.

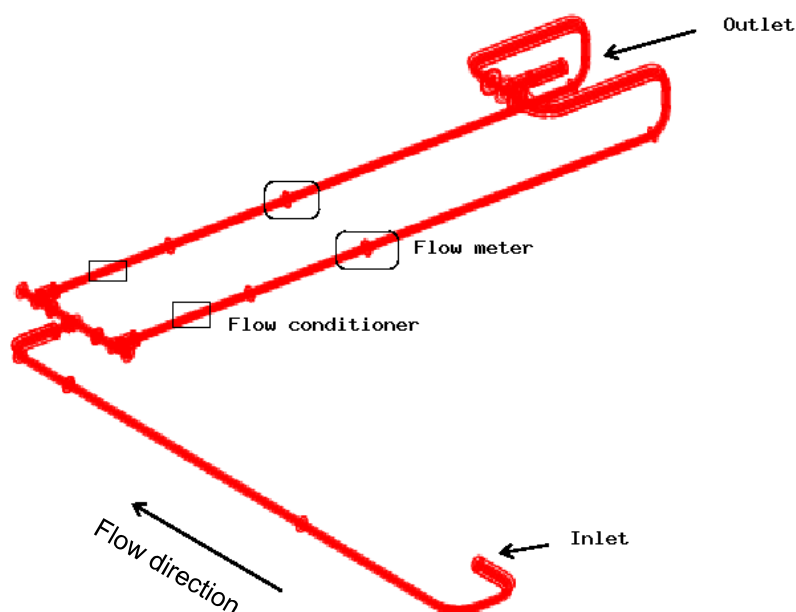


Figure 2.3 Simulation geometry of the metering station with T-bends at the header, parallel operation.

2.5.2 Simulation parameters and reference base case

The simulation parameters were based on the typical values of the USM gas export metering station:

- Velocity 9.5 and 19 m/s
- Pressure 149 bar
- Temperature 51.5 °C
- Density 139.3 kg/m³
- Viscosity 1.86·10⁻⁵ kg/ms
- Pipe spool diameter 288.53 mm
- Reynolds numbers 2·10⁷ and 4·10⁷

The simulations referred to as *Base case*, are for fully developed flow in straight pipe. The velocity profiles derived from the MUSIC CFD simulations are symmetric axial velocities, and transversal velocities approximately equal to zero. The USMSIM analyses of MPU 1200 calculates for the Base case a flatness as function of Reynolds number, symmetry of 0.001 %, swirl of 0 %, and cross-flow of 0 %. Initially the simulations were performed assuming smooth walls (roughness of 0.01 mm). For Reynolds number in the range of 2-4·10⁷, the flatness of developed flow in this case will be approximately 95 %. This is considered to be a high value, and the simulations were repeated with higher roughness values. The roughness value is equivalent to the grain size of the sand corns on a sand paper coating the inner walls of the pipe. In the calibration tests, the reported profile flatness from the MPU 1200 was typically 90 % and constant over the meter velocity range. Test simulations in a very long straight pipe giving developed flow profiles were carried out with different wall roughness. The flow profiles were then run through USMSIM. Based on the evaluation of flatness for different types of roughness values, the simulations were performed with an assumed coefficient of roughness set to 0.3 mm.

2.5.3 Simulation results: piping configuration with regular bends

Flow simulations were carried out for simple piping configuration in order to investigate effects of swirl on the USM flow meter. These simulations were compared to the fully developed flow pattern, referred to as *base case*. The effect of swirl on the volume flow depends on the orientation of the swirl relative to the meter. Hence, a specific swirl value will not have a unique effect on the volume flow reading. From the simulations, an absolute swirl value of 2 % would have an effect spanning over 0.3 % on the volume flow reading, depending on the orientation of the swirl relative to the meter.

Simulations were performed with regular 90° bends instead of T-bends in the header of the flow metering station. The upstream piping configuration were kept similar as is, with a clock-wise snail house orientation.

Figure 2.4 shows the simulated flow velocities in the horizontal cross section of the 90° bend and first section of run 2, single operation. The initial velocity of the simulations were 19 m/s. For a configuration with regular bends, there is no sign of recirculation zones in run 2, neither in run 1 during single operation.

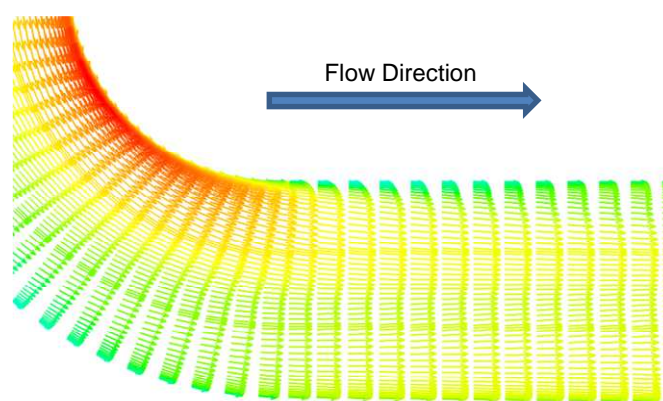


Figure 2.4 Flow velocities in the entrance of run 2 single operation, regular 90° bends. The flow pattern is shown in a horizontal plane through the meter pipe axis. It is shown as vectors at each grid point. Blue means low flow, yellow and red means higher flow.

2.5.4 Simulation results: piping configuration with T-bends in the header

Simulation of the metering station as is, with T-bends at the header, but without the flow conditioner, showed the following:

- Parallel export: Recirculation zones with negative flow velocities in part of the pipe cross-section downstream of the T-bends of the header. Especially prominent for run 2. The recirculation zone for run 2 extends over 1 m downstream of the manifold. The flow conditioner is at 1.8 m from the manifold. For run 1, the simulated swirl is 4 %, and for run 2 the simulated swirl is -5 % at the flow meter position. Note that these simulations were performed without flow conditioner. Simulated swirl are significantly larger than observed, as expected, since the flow conditioners should smooth the flow and reduce swirl.

- Single export through run 1: Recirculation zones after the T-bends of the header are more prominent than for parallel export. At the position of the flow conditioner, 1.8 m from manifold, the flow profile symmetry parameter indicates an asymmetric flow profile.
- Single export through run 2: Recirculation zones after the T-bends, as for single export run 1. Disturbed flow with significant asymmetric flow is present also at the position of the flow conditioner. Note again that these simulation results are performed without flow conditioner.

The flow recirculation, which was found in the simulations of the metering station with T-bends, was not found in the simplified geometry with ordinary 90° bends (see Figure 2.4). The flow recirculation region and the flow profile further downstream (1.8 m from the manifold) appear to be quite different in run 1 compared to run 2.

The main difference between run 1 and run 2 from the results of the simulations of flow without flow conditioner: The flow profiles at the position 1.8 m from the manifold are in a way inverse of each other, where the flow at a position in the cross section of the pipe in one of the run is low, it is high in the other run, and vice versa.

2.5.5 Simulation results: piping configuration as is with flow conditioner

Simulations were performed of the metering station as is with flow conditioner present 1.8 m from the manifold. The three-dimensional flow profile, including flow effects like swirl, was found, and the equivalent measurements of the flow meter were found by use of the USMSIM program. The distance between the flow conditioner and meter is 15 D.

The flow conditioner (FC) is a CPA (Canadian Pipeline Accessories) plate with 25 holes. The pressure build-up on the upstream side of the plate will act to redistribute skew axial flow profiles. The flow will emerge from the holes on the downstream side as jets from each hole. The high turbulence levels will quickly mix the jets and give a developed profile. It is, however, possible that the asymmetries of the flow can propagate through the flow conditioner and give a reduced symmetry on the downstream side.

The simulations showed recirculation regions, with flow in reverse direction in part of the pipe cross section, at the beginnings of the meter pipes as in the simulations of the meter station without the flow conditioners. This is believed to be a result of the T-bends between the manifold and the meter pipes. The recirculation is shown in Figure 2.5, for single export in run 1, and in Figure 2.6, for single export in run 2. The flow pattern is shown in a horizontal plane through the meter pipe axis. It is shown as vectors at each grid point of the CFD simulations. Blue colour means low flow, whereas green and yellow mean higher flow, up to a maximum at yellow of 58 m/s. The recirculation zone with reverse flow is marked within the red line in the plot. The simulation results indicate that the nature of the recirculation region and the flow profile downstream that region is quite different in run 1 compared to run 2 when single export.

The simulation results with the flow conditioner as positioned in the metering station, show that the swirl and cross flow are close to zero for all orientations of the USM relative to the flow. The deviation from reference simulations of fully developed flow,

is estimated to be between 0 and 0.3 % for single export through run 1, and between -0.1 and 0.4 % for single export through run 2.

The simulated profile symmetry, flatness, and deviation varies with the orientation of the flow profile relative to the USM.

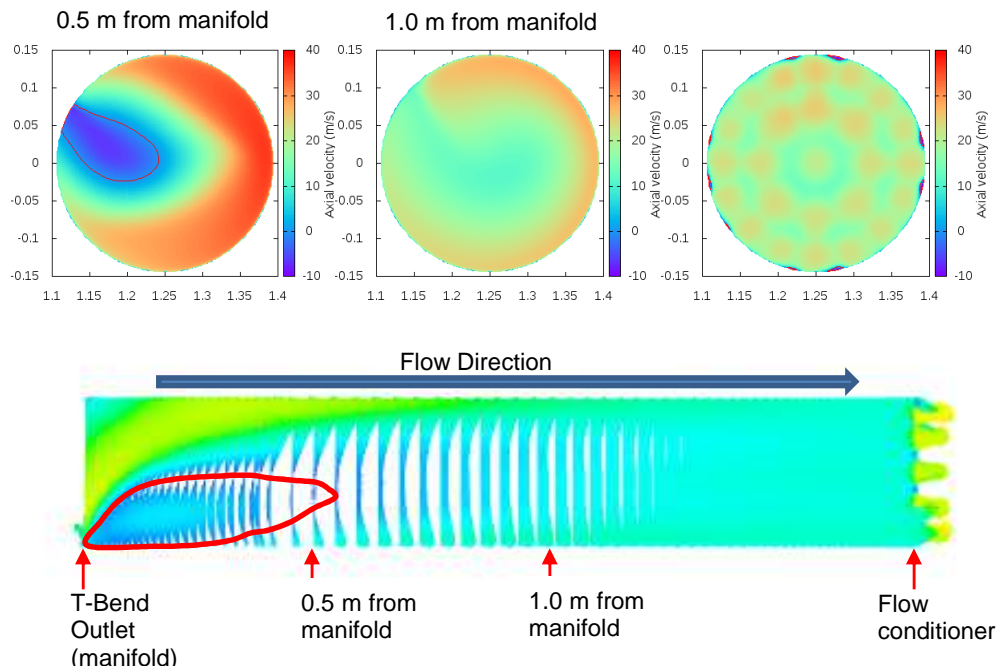


Figure 2.5 Simulation results for run 1 single export. Upper part: axial flow profile 0.5 m, 1.0 m and 1.8 m downstream the manifold. Lower part: Flow velocities in run 1 between the manifold and the CPA-plate (flow conditioner). The flow pattern is shown in a horizontal plane through the meter pipe axis. It is shown as vectors at each grid point. Blue means low flow, green and yellow means higher flow. The recirculation zone (with reverse flow) is marked in red.

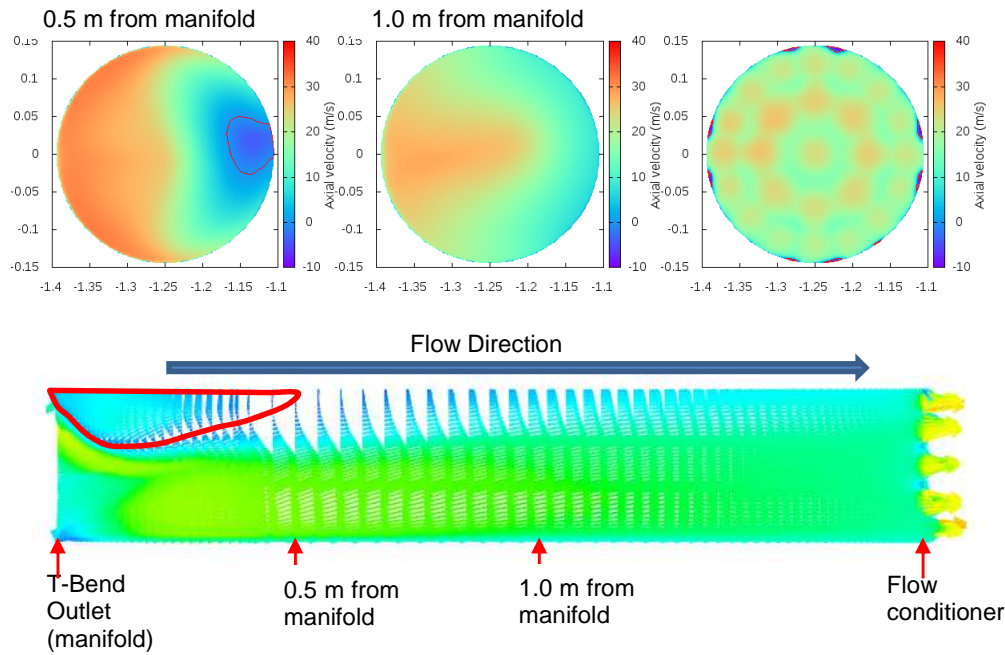


Figure 2.6 Simulation results for run 2 single export. Upper part: axial flow profile 0.5 m, 1.0 m and 1.8 m downstream the manifold. Lower part: Flow velocities in run 2 between the manifold and the CPA-plate (flow conditioner). The flow pattern is shown in a horizontal plane through the meter pipe axis. It is shown as vectors at each grid point. Blue means low flow, green and yellow means higher flow. The recirculation zone (with reverse flow) is marked in red.

The simulated flow pattern at the location of the USM for the given piping configuration with the existing flow conditioner shows a low value of the swirl and cross flow for both lines, single operation. The other flow parameters vary with the orientation of the flow profile relative to the USM. This variation seems to be more prominent in run 2, single export. The deviation from reference volume flow reading is in the range of 0.3 to 0.4 % for both lines based on simulation of the metering station as is. Figure 2.7 shows the simulation result of the axial velocity profile at the position of the meter for single export for run 1 (left) and run 2 (right).

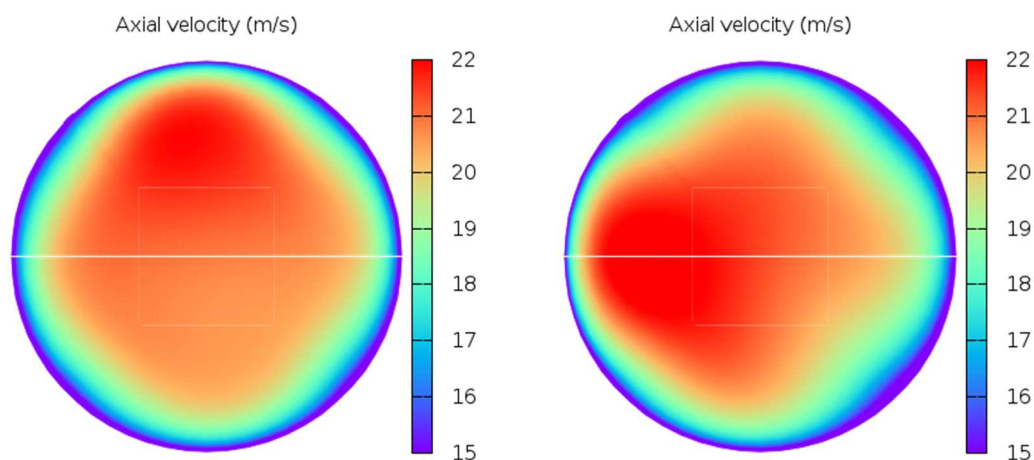


Figure 2.7 Axial velocity profile at position of meter, simulations of metering station as is, with flow conditioner. Left: Single export, run 1 open, Right: Single export, run 2 open.

The simulations showed the occurrence of a recirculation zone between the T-bend header and the flow conditioner. There are major differences between the flow profiles upstream of the CPA-plate in run 1 compared to run 2. It might be that this causes the observed peaks in run 2, as this region probably varies with the variations in the flow.

The CFD simulations may have overestimated the effect of the flow conditioner plate since both swirl and cross flow appear to be almost zero at the meter position, for both lines. However, the flow profiles upstream of the flow conditioner more likely indicate that there is a large flow profile difference between run 1 and run 2.

2.5.6 Simulations of a possible optimum location of the flow conditioners

The simulations of the metering station as is were repeated for other locations of the flow conditioner in order to search for a more optimal location of the flow conditioner. The results presented here are with the flow conditioner positioned 8.5 D upstream of the USM. The initial distance between the flow conditioner and meter is 15 D.

The flow velocities between the manifold and the CPA-plates (at new position) are shown in Figure 2.8 and Figure 2.9. The recirculation at the entrance to the meter pipes persists as in the simulation with the CPA-plates at the present location. However, the flow will tend to smooth out and become more uniform upstream of the flow conditioner plate with the modified flow conditioner position. This may possibly lead to less occurrences of peaks, which are observed in run 2.



Figure 2.8 Flow velocities in run 1 single operation between the manifold and the modified position of the CPA-plate. The vectors are shown in a horizontal plane through the meter pipe axis. Similar plot as Figure 2.5, but with flow conditioner 3.8 m after the manifold.

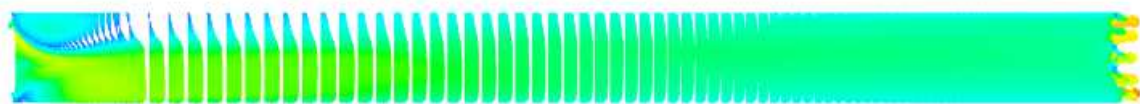


Figure 2.9 Flow velocities in run 2 single operation between the manifold and the modified position of the CPA-plate. The vectors are shown in a horizontal plane through the meter pipe axis. Similar plot as Figure 2.6, but with flow conditioner 3.8 m after the manifold.

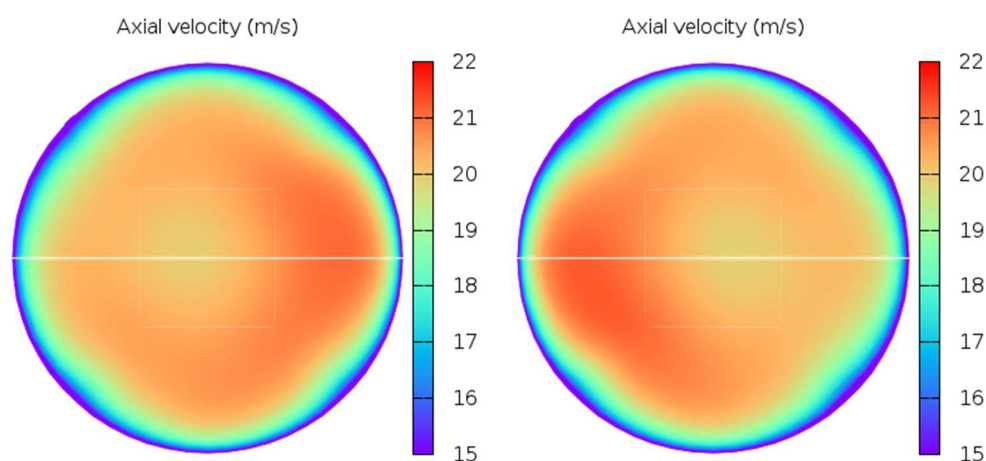


Figure 2.10 Axial velocity profile at position of meter, simulations of metering station as is, with flow conditioner in new position 3.8 m from header. Left: Single export, run 1 open, Right: Single export, run 2 open.

The simulated flow pattern at the location of the USM for the given piping configuration with the existing flow conditioner shows a low value of the swirl and cross flow for both lines, single operation. The other flow parameters vary with the orientation of the flow profile relative to the USM. This variation is lower than the results when the flow conditioner was placed 1.8 m from inlet (as is). This may indicate that a positioning of the flow conditioner closer to the flow meter gives a less disturbed flow pattern than the installation as is. Figure 2.10 shows the simulation result of the axial velocity profile at the position of the meter for single export for run 1 (left) and run 2 (right), when the flow conditioner is placed 3.8 m from header.

The recirculation zones between the T-bend header and the new positioned flow conditioner, seem from simulations to be more smooth also for run 2, and the flow is more uniform upstream of the plates with the modified position. Although the simulations at hand did not show any peaks, since the simulations run were stationary, it is found probable that a new location of the flow conditioner further away from the T-bend header will provide more stable flow conditions.

3 CONFIGURATION ERRORS, EVALUATION OF EFFECTS

In this chapter, the effect of wrong input for the configuration files of the flow meters is discussed, and the calculated results expected for a correctly implemented flow meter for Gjøa gas export are presented.

3.1 Configuration files – error in parameter values

The flow meters installed at the Gjøa gas export station, measure six flow velocities, or path velocities. These six path velocities are combined with weight factors specified for the meter in order to calculate the average axial flow velocity.

For the meters at Gjøa gas export metering station, the configuration of the inclination angles of the sound paths were correct for the double set transducers of acoustic paths 1, 3, 2 and 4. For the two lower sound paths, however, the inclination angles in the configuration file were implemented with opposite sign than the actual design of the meter.

For the flow profile parameters, flatness and symmetry will depend on the inclination angles and weight factors defined in the configuration of the meters. Whereas for the calculated swirl value, cross flow value and velocity of sound, there are close to no dependency of the specified inclination angles and weight factors for the two lower acoustic paths.

The consequence of the wrong sign on the inclination angles for acoustic paths 5 and 6 is that the correction of transversal flow components, that is swirl and cross flow, was performed with the wrong sign.

3.2 Analysis of effect of error

In the analysis of the effect of error in the configuration setup of the meters, an evaluation of the metering results was calculated as if the correct angles had been used in the software.

Figure 3.1 shows an example of single export in run 2, with the flow velocity measured by the meter with wrong inclination angles for the two lower acoustic paths in orange, and how the flow velocity would have been if correct angles were implemented, shown in blue. For the example presented here, there is a peak in the time series of the observed flow velocity. Note that with the incorrect angles as implemented, this jump in flow velocity was in the range ~0.3 to 0.4 m/s. Now, if correct angles were implemented the jump in flow velocity would have been in the range ~0.1 to 0.2 m/s. Thus, the effects of the peaks in run 2 are not as severe with correctly implemented inclination angles.

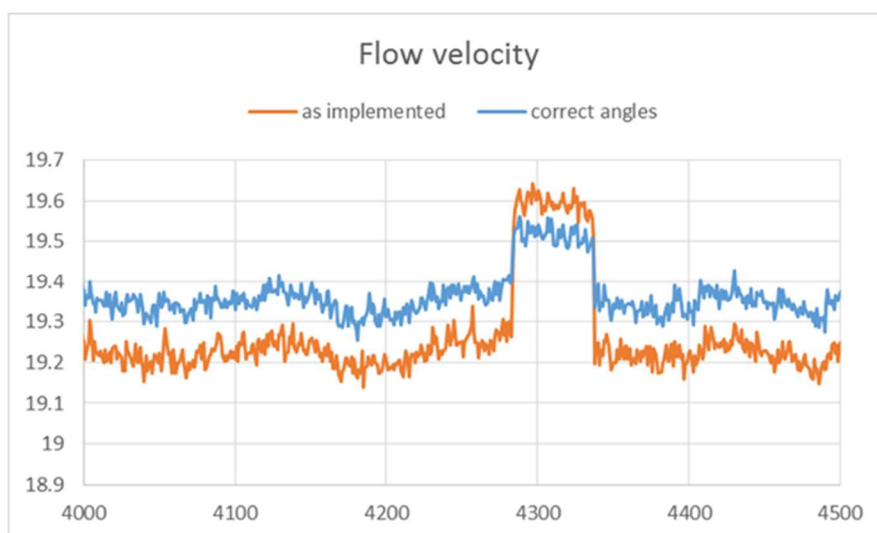


Figure 3.1 Example of the implications of the wrong inclination angles, single export run 2. Y-axis displays the flow velocity in m/s, and x-axis is time. In orange: The metering result as implemented. Blue: The metering result if correct angles had been used.

Figure 3.2 shows the deviation between the measured total flow velocity as implemented relative to how it should have been with correct angles for single export in run 2. For this example, two peaks were apparent in the observed flow velocity. In general, for this example, the flow velocity was underestimated with approximately -0.6 % during regular flow, and overestimated by approximately 0.4 % when peaks

appeared in the flow. Note that these calculations are performed based on the measured flow velocity for each acoustic path and their correctly corresponding weight factors. The influence of calibration factor on the measurement results when the calibrations were performed with errors in the configuration files is not included here.

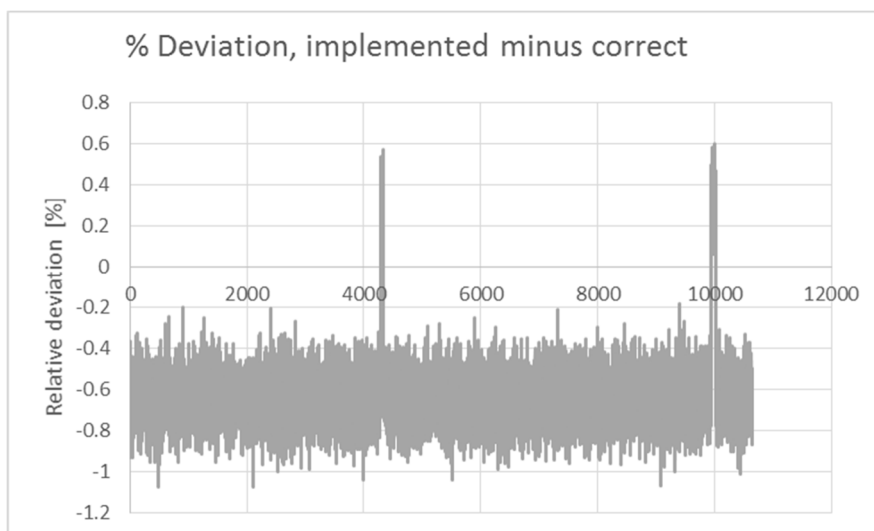


Figure 3.2 *Deviation between measured total flow velocity with angles as implemented relative to correct angles. Example with single export in run 2.*

A detailed analysis of the flow parameters derived from the USM measurements, indicated that the flatness was more stable and at a higher value than for the measurements with wrong inclination angles for the two lower acoustic paths. There were no signs of change in the flatness value during peaks. The symmetry was also more stable and with a lower value than for the result as implemented. The peaks are shown as dips for the symmetry value. However, the amplitude of the dip relative to the stable level is significantly reduced when correct angles are used in the calculations. Calculated flow parameter values for swirl and cross flow are not affected by the switched sign in inclination angle for the two lower paths.

3.5 Configuration errors – what about flow calibration?

The flow meters were calibrated with the incorrect inclination angles. How does this affect the measurement results of the separate axial flow velocities for each of the six acoustic paths?

If there are swirl and cross flow present during calibration, although minor, the effect would have been enhanced by the opposite sign of the inclination angles. Investigation showed that with a swirl value of 0.10 % and cross flow of -0.12 %, the result would be a 0.26 % shift in the calibration K-factor. If the swirl values were as low as 0.02 % and cross flow -0.04 %, the shift would have been 0.09 %.

Hence, the effect of shift from the calibrations are also included in the correction of the flow measurements in order to meet the fiscal requirements.

4 CONCLUSIONS

This paper describes the evaluation of installation effects and flow instabilities in the Gjøa gas metering station, which consists of two parallel runs with multipath ultrasonic flow meters. The analysis was carried out based on Computational Fluid Dynamics (CFD) with additional calculation of the metering results of the flow meters in use. The study also covered the evaluation of errors in the meter configuration file, how it affected the meter performance and factors derived from calibration.

The results of the CFD analysis of the metering station geometry, with the upstream conditions equivalent to the Gjøa gas export metering station, showed that the geometry of the header and pipe geometry upstream the header can affect the flow stability through a flow meter. The positioning of the flow conditioner can therefore be of high importance.

The limitation of space on the metering site might require the upstream piping to be not ideal for the metering principle at hand. However, with an evaluation of the expected effects on the flow geometry at the positions of the meters, the functionality of a six beam ultrasonic meter may be optimized with an evaluation of the upstream header and positioning of the flow conditioner.

The measurement errors caused by errors in the flow meter configuration file, can be corrected for based on the initial ultrasonic measurements for each acoustic beam. This, naturally, will rely on the frequency of which the original ultrasonic measurement data are stored. The evaluation based on the initial axial flow velocities measured for the six acoustic beams, showed that the ultrasonic flow meter provides acceptable fiscal measurements of the flow for the Gjøa gas export.

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6 References

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