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Installation Effects on the Easington Ultrasonic Fiscal Metering Station

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1 INTRODUCTION

The gas from Norway's Ormen Lange gas field is imported to UK at the Langeled Receiving Facilities (LRF) in Easington. This section of the terminal is operated by Centrica on behalf of Gassco. Eventually up to 25 % of the UK gas demand may be served from this pipeline alone. The fiscal metering station for the Ormen Lange gas consists of ultrasonic meters installed in four parallel meter pipes. The design has some deviations from the conventional design, i.e. no flow straightening devices and long upstream lengths (~55D) to the metering point. At the ultrasonic flow meters, asymmetric velocity profiles are observed. Because of the possibility of increased uncertainty in the measured gas amount due to these asymmetries, CMR and Gassco have carried out an investigation of the installation effects of the metering station at Easington.

In the present work, the results from this investigation are presented. A Computational Fluid Dynamics (CFD) model for the inlet header and the metering sections is established, and simulations are carried out covering a range of flow rates. To investigate the sensitivity of the meters to flow variations in header, different inlet flow velocity profiles including rotation are applied. Measurement configurations with all four metering sections in use and with one or two metering sections closed are covered. Comparisons show good agreement between the CFD analyses and the measurement. The calculated flow velocity fields are thereafter taken as input to a computer program where the ultrasonic flow meter is modelled. Here the average velocities along the sound paths are calculated as well as an accurate estimate of the average (reference) flow velocity. The integration algorithms used in the flow computer are applied to calculate the average velocity from the sound path velocities, and the results are compared with the reference velocities. Other parameters like swirl are also considered. In addition to the results at the meter locations, virtual meter installations upstream in the metering sections are also considered. In the bulk of the cases, the deviation from the flow calibration (simulated) for the four ultrasonic flow meters is in the range 0.05-0.25 %. For all cases except one, the deviations from reference at the meter installations are less than ± 0.3 %.

2 INSTALLATION GEOMETRY AND FLOW DATA

The metering station and the upstream piping are shown in Figure 1. It is there seen that the header is asymmetric (when considering the inlet relative to the four metering sections). This layout has been made in order to achieve easy access to all meters and associated instrumentation from two different platforms. The simulation geometry starts at the header inlet, position A in the figure, and ends in the manifold downstream of the 4 parallel metering sections, position B in the figure. Each of the metering sections can be closed by valves, position C in the figure.

The four parallel metering sections are each equipped with an FMC MPU1200 ultrasonic flow meter [1]. The calculations of the flow will be carried out from the inlet of the metering header, through all four metering runs and through the pipes and manifold downstream of the meters.

The inlet valve of each metering section is set to be totally open, and the unit is modeled as an empty pipe.

The inner diameter of the header pipe is 0.987 m. In the metering section, the inner diameter is 0.560 m (~24"). At the manifold downstream the metering sections, the inner diameter is set to 0.987 m.

The bend between the header and each of the parallel metering pipes has a bend radius of 1.71 m. The bend radius in the header pipe S-bend is set to 2.75 m.

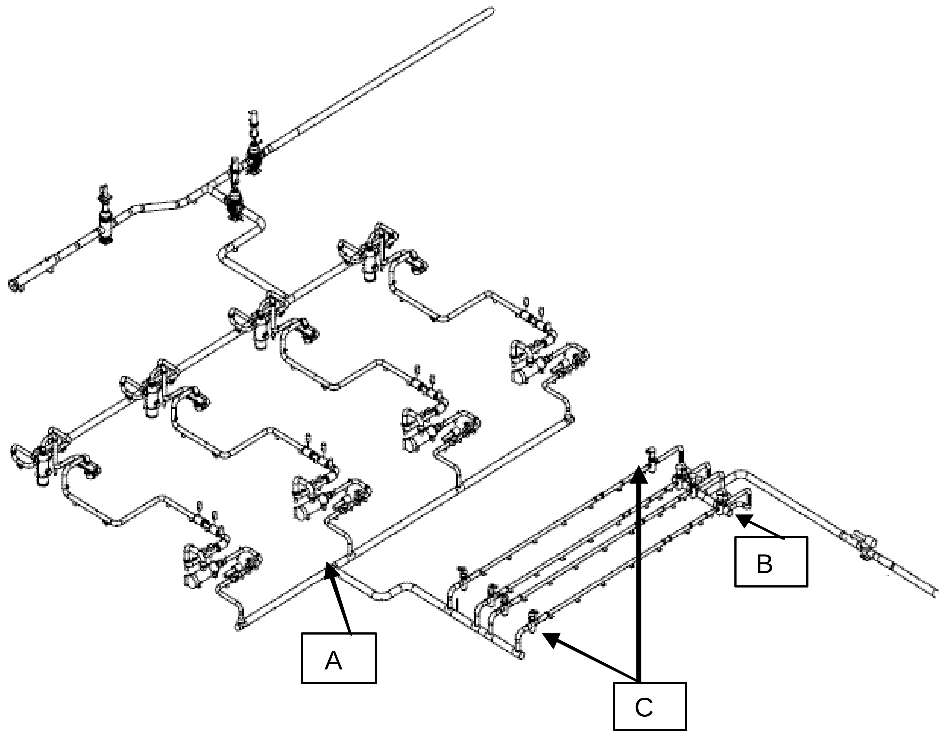

Figure 1 *Geometry of the Easington measurement station. The CFD simulation geometry starts at the header inlet at the position marked A, and ends in the downstream manifold marked B.*

The actual gas pressure, temperature and density in the measurement station are typical values from a given day, and can be considered to be representative for the conditions at the metering station. The gas viscosity is set to a typical value for dry natural gas. The gas flow velocities at the header are chosen to cover the variations to be expected in reality. The values are given in Table 1 .

Table 1 Flow parameters

Parameter	Value	Unit
Gas temperature	5.5	^oC
Gas pressure	64	*bara*
Gas density	60.6	kg/m^3
Gas viscosity	1.5×10^{-5}	$kg/m \cdot s$
Gas velocities (header)	5-10-15-20	*m/s*

Several configurations of the metering station have been used. Measurements have been carried out with 4, 3 and 2 active pipes. With 3 active pipes simulations with pipe 1, 2 and 3 respectively 1, 3 and 4 have been run. Here, pipe 1 refers to the first pipe to branch off the header etc.

An overview over the flow velocities and the Reynolds number for the different configurations is shown in Table 2. It is here assumed that the flow is evenly distributed between the individual pipes. It will be shown later that both measurement and simulations predict that the flow rate differs consistently up to 25-30 % between the individual pipes. For 4 and 3 active pipes the highest velocity is found in the header, with 2 active pipes the metering section velocity is highest. For all configurations the highest Reynolds number is in the header. The Reynolds number in the metering section is in the range $9 \cdot 10^6$ to $8 \cdot 10^7$.

Table 2 Average velocities and Reynolds number for different measurement configurations and flow rates. It is assumed that the flow is evenly distributed over the pipes.

	Velocity (m/s)				Reynolds number (-)			
Header	5	10	15	20	$2x10^7$	$4x10^7$	$6x10^7$	$8x10^7$
Pipe – 4 runs	3.9	7.8	11.6	15.5	$9x10^6$	$1.7x10^7$	$2.5x10^7$	$3.5x10^7$
Pipe – 3 runs	5.2	10.4	15.5	20.7	$1.2x10^7$	$2.3x10^7$	$3.5x10^7$	$4.7x10^7$
Pipe – 2 runs	7.8	15.5	23.3	31.0	$1.7x10^7$	$3.5x10^7$	$5.2x10^7$	$7x10^7$

3 SIMULATION MODEL

3.1 CFD Simulation Model

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], [3], [4], [5].

In the simulations the gas is considered to be incompressible. The flow pressure variations are small relative to the pressure level of 64 bara, and the corresponding changes in gas density are also small.

In the simulations, equations for momentum (Navier-Stokes) and pressure are solved together with the equations for the industry standard $k-\omega$ turbulence model. Due to the high Reynolds numbers, the turbulent boundary layers at the pipe walls are thin. The wall friction is therefore modelled with wall functions. The wall is assumed to be smooth.

The numerical grid is made up by hexahedron (brick) control volumes. Up to 1.2 million volumes have been used in the simulations.

In the bulk of the simulations, the complete metering station including the pipe manifold has been part of the geometry. It is then not necessary to make any assumptions of the flow rate in each of the up to 4 metering sections, the flow rate in each pipe will be a result of the simulation. Differences in pipe flow rates will be a result of the total friction and pressure losses in the pipe network. In some simulations the mass flow rate at the end of each metering section has been set to measured or simulated values. The manifold can then be excluded from the simulation geometry. This makes it possible to use a higher grid resolution to increase the accuracy of the results.

To simplify the calculations when the total geometry including the pipe manifold is used, the outlet from the manifold is modelled as a mass sink in the manifold centre. This is considered to have little, if any, influence on the flow rate distributions in the meter runs. Also the influence on the flow profiles at the meter positions is negligible, since there are several pipe diameter distance from the flow meters down to the manifold centre.

At the inlet of the header (point A in Fig. 1) a developed axial flow profile taken from a simulation in a pipe with the header diameter and the relevant average velocity is used. In addition to the results shown here, also the case with a swirl flow at the header inlet is analyzed.

For the simulations with 3 or 2 metering section pipes in operation, the part of the closed pipe from the T-bend up to the closed valve is removed in the simulations, and the T-bend replaced with a pipe section. The same practice is also used in the downstream manifold. This simplifies and reduces the CPU-time in the simulations. The influence of this simplification on the flow rate distribution and the velocity profiles through the flow meters in the active pipes is also small.

3.2 USM Simulation Model

The flow profiles calculated by the *MUSIC* CFD code are afterwards used as input to a program for calculation of the flow profile effect for the ultrasonic flow meters in question. This analysis is based on the *USMSIM* program in the GARUSO package [6], see also [7] and [8] for related works. In this program, the average flow velocities (including the effects of the transversal flow velocity components) are calculated for each of the 6 acoustic paths of the FMC MPU 1200 ultrasonic flow meters in question. Thereafter, the integration algorithm in the MPU 1200 is applied to calculate the “measured” average axial flow velocity over the pipe cross section in the flow meters, based on the calculated average flow velocities over each of the 6 acoustic paths.

In the *USMSIM* program for simulation of the ultrasonic flow meter, cubic spline approximations are set up for the CFD-calculated flow velocity profiles in the meter cross section. The interpolation along the sound paths can then be carried out to a high accuracy. The reference average axial velocity is calculated from an accurate numerical double integral.

Details on the MPU 1200 integration algorithm specifying the positions and angles of the sound paths are supplied to Gassco from the FMC. The actual integration weights of the MPU 1200 are used with permission from FMC. These values are given as inputs to the USMSIM program.

4 FLOW SIMULATION RESULTS

The metering station is typically operated with 3 of the 4 metering sections in use. In periods the metering station is also operated with 2 or 4 metering sections in use.

Flow simulations from the header inlet and through the metering station are carried out for the following situations

- All 4 metering section pipes (pipes 1, 2, 3 and 4) are in use
- Pipes 1, 2 and 3 are in use, pipe 4 is closed
- Pipes 1, 3 and 4 are in use, pipe 2 is closed
- Pipes 3 and 4 are in use, pipe 1 and 2 are closed

Here pipe 1 refers to the first pipe to branch off the header etc.

4.1 All 4 Metering Sections In Use

The metering station is simulated with average inlet velocities of 5, 10, 15 and 20 m/s. The resulting surface relative pressure distribution[1], which also displays the pipe geometry, is shown in the upper part of Figure 2 for an average inlet velocity of 10 m/s. The maximum deviation from the 64 bara initial pressure is 0.14 bar, or 0.2 %. This shows that the incompressibility approximation is reasonable, as the corresponding variations in density would have the same deviation from the constant value. Even for an average inlet velocity of 20 m/s the maximum deviation is less than 1 %.

The flow velocities in the junctions between the header and the measurement runs are shown in the lower part of Figure 2. The flow velocity in the header will diminish after each pipe

[1] Relative to the 64 bara pressure level.

diversion as the flow rate in the header is reduced. It is also seen that the T-bends in combination with the following 90° bends acts as swirl generators, as expected.

The transverse, rotating flow is shown in the left part of Figure 3 at three different axial positions (8, 30 and 55 diameters downstream the last bend) in pipe 1 with an average inlet velocity of 10 m/s in the header. It should here be noted that the ultrasonic flow meters are installed about 55 diameters downstream the last bend. As expected, the transversal flow velocity components correspond to a swirl, and decrease downstream from the bend. However, the maximum transversal flow velocity is still 7 % of the average axial velocity at the ultrasonic flow meter installation position 55 diameters downstream the last bend. The swirl is asymmetric close to the bend. It becomes more symmetric at the meter installation position.

The axial flow velocity at the same three axial positions (8, 30 and 55 diameters downstream the last bend) in pipe 1 is shown in the right part of Figure 3. The average inlet velocity in the header is 10 m/s as for the transversal flow velocity profiles discussed above. The axial flow velocity profile is seen to be asymmetric. It is seen to be rotating downstream the pipe, when comparing the flow profile at the three axial positions. This is due to the swirly transversal flow component that also will rotate the axial flow profile. As for the transversal flow velocity profile, the asymmetry of the axial flow velocity profile decreases as the distance from the bend increases.

Due to the asymmetric configuration of the metering header, the flow distribution between the 4 metering section is not expected to be uniform. This is shown in Figure 4. There the CFD calculated average flow velocities in each metering section are shown on a relative scale for the 4 inlet header flow velocities in question (5, 10, 15 and 20 m/s). The flow rate (velocity) is lowest in pipe 1, which is the first branch to the header. The flow rate is larger in pipe 2, even larger in pipe 3, and then lower in pipe 4. The CFD simulations indicate that the relative flow distribution over the pipes is independent of flow rate. The variation in flow rate is due to a combination of local flow conditions in the T-bend junction together with the line friction and pressure losses due to pipe bends and entrance losses to the manifold. In addition to the results from the CFD simulations, measurements from the metering station when all four metering sections are in use are shown. In this case, the inlet header velocity is 5.7 m/s. It is seen that qualitatively, the measurements show the same distribution in flow velocity over the four metering section as found from the CFD simulations. Quantitatively, the largest difference is seen for pipe 1.

4.2 2 or 3 Metering Sections In Use

In order to cover normal operation configurations of the metering station, also simulations with 2 or 3 metering sections in use have been carried out. For 3 metering sections in use two configurations have been simulated. These are:

- Pipes 1, 2 and 3 are in use, pipe 4 is closed
- Pipes 1, 3 and 4 are in use, pipe 2 is closed

In addition the following configuration with 2 metering sections has been simulated:

- Pipes 3 and 4 are in use, pipe 1 and 2 are closed

As for the case with all 4 metering sections in use, CFD simulations have been carried out for average inlet velocities at the header of 5, 10, 15 and 20 m/s.

For simplicity, only results for the relative flow distribution between the pipes are presented here. In Figure 5 the results for the two configurations with 3 metering sections in use are shown. As for the case with all 4 metering sections in use, there is an asymmetry in the velocity distribution between the metering sections. It is also seen that the correspondence between simulations and measurements is good.

In Figure 6, the similar results are shown for 2 metering sections in use. In this case, no comparisons with experimental results have been carried out.

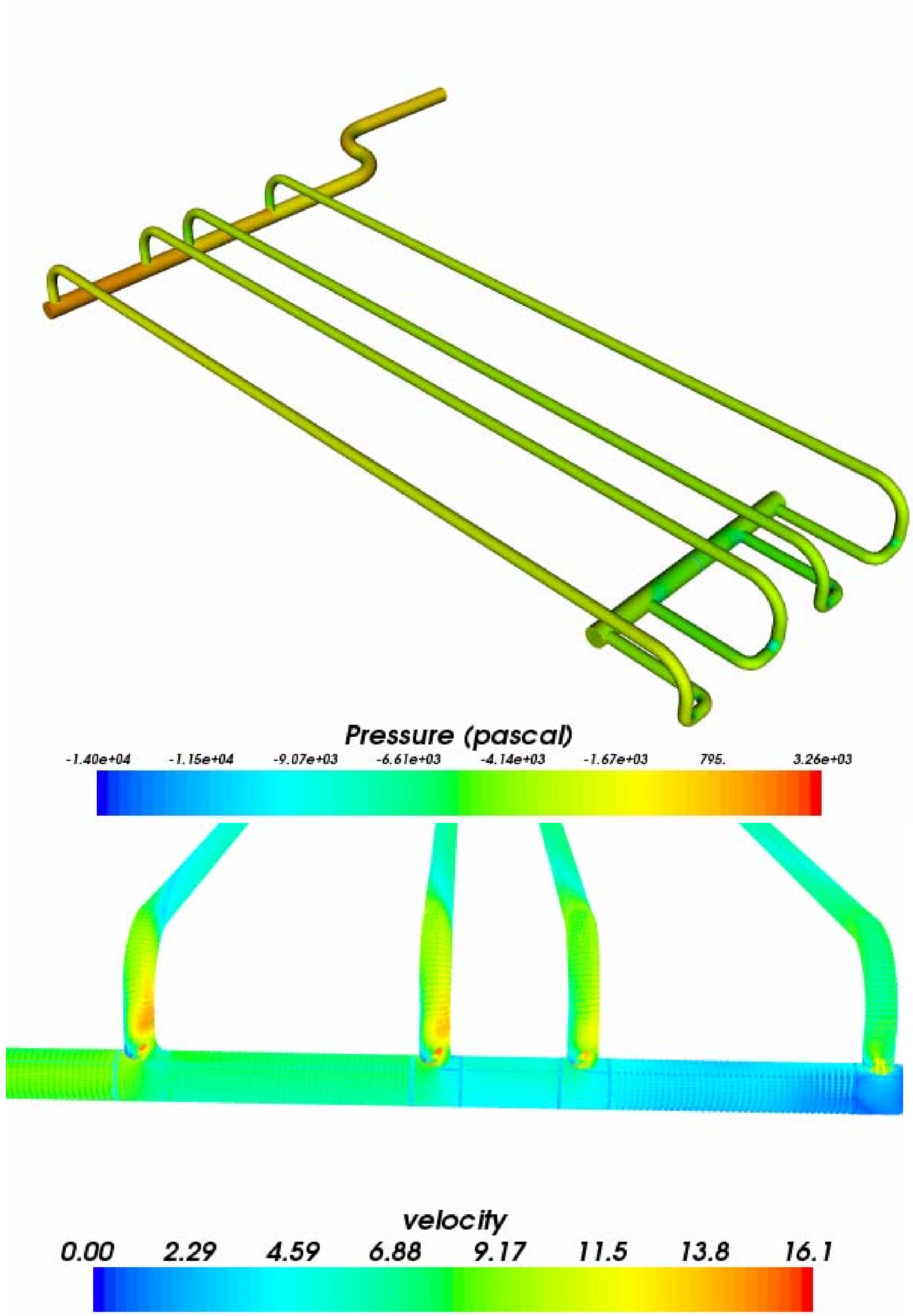

Figure 2 Upper figure: Plot of pipe surface relative pressure. The difference between maximum and minimum pressure in the geometry is 0.17 bar, and the differential pressure between inlet and manifold 0.08 bar. Lower figure: Velocity vector magnitude. It can be seen that the T-bends in combination with the 90^o bends generates rotation. In both cases the average inlet velocity of the header is 10 m/s.

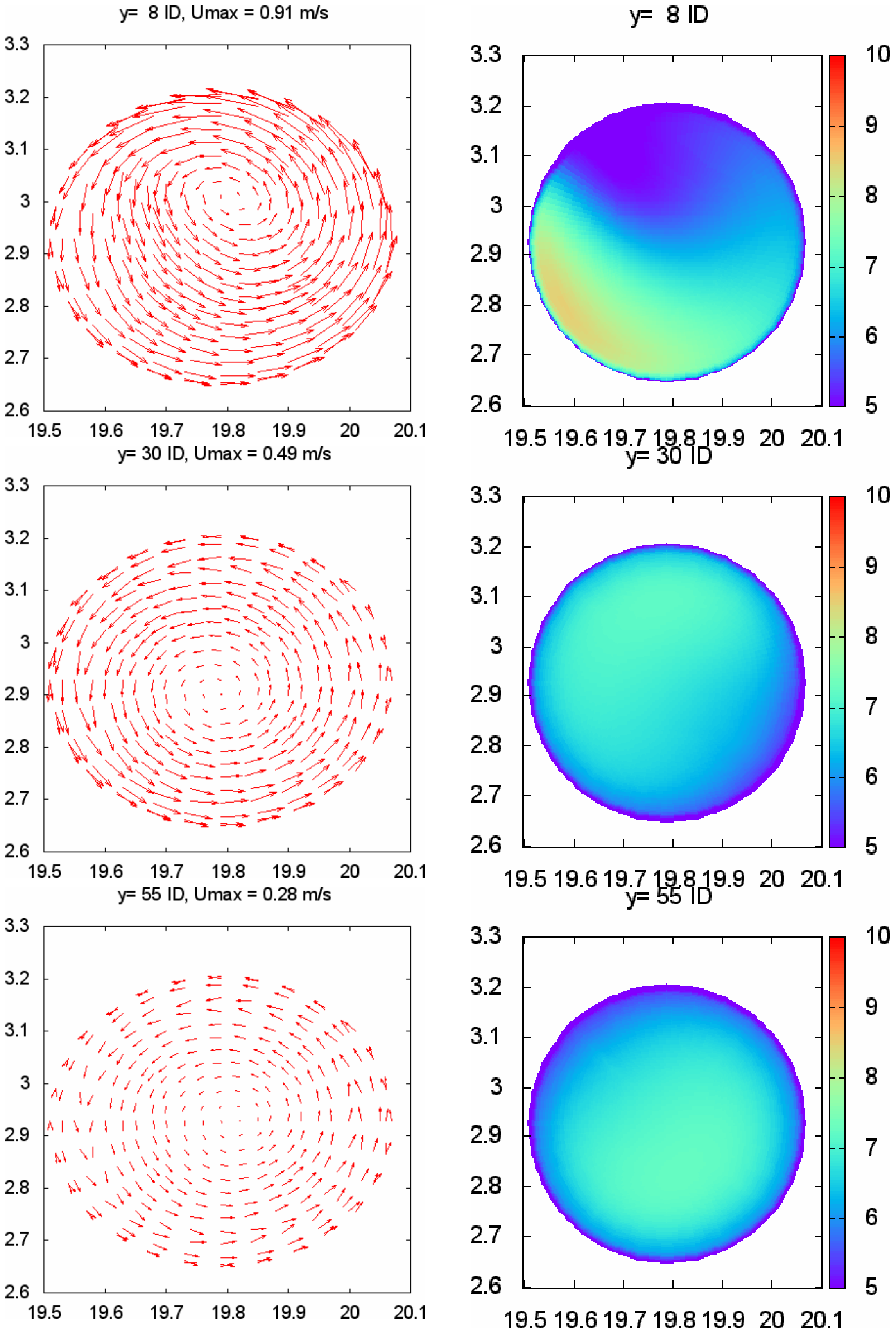

Figure 3 *CFD simulated transversal (left) and axial (right) flow velocity profiles in pipe 1 in a cross-sectional cut plane at 8, 30 and 55 diameters downstream the bend. The header velocity is 10 m/s. The view direction is downstream towards the meter. The ultrasonic flow meter is located about 55 diameters downstream the bend.*

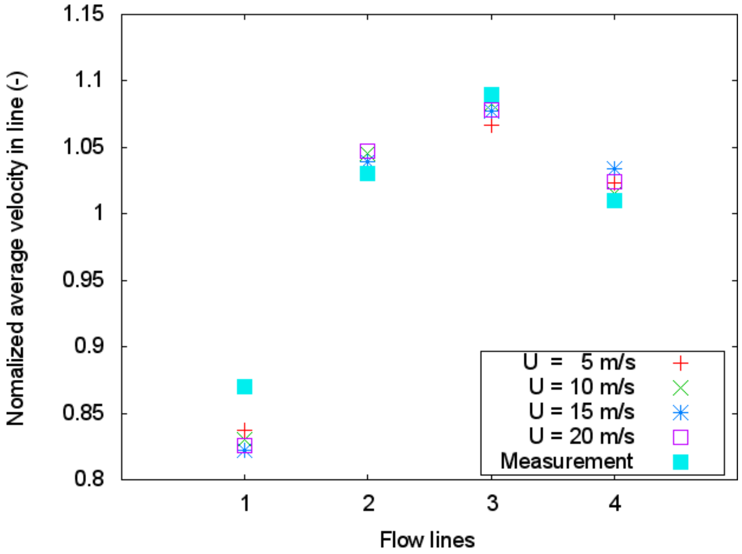

Figure 4 *CFD simulated and measured relative flow distribution over the different metering sections when all metering sections are in use. Flow line 1 is the first branch to the header, the other are numbered in increasing order.*

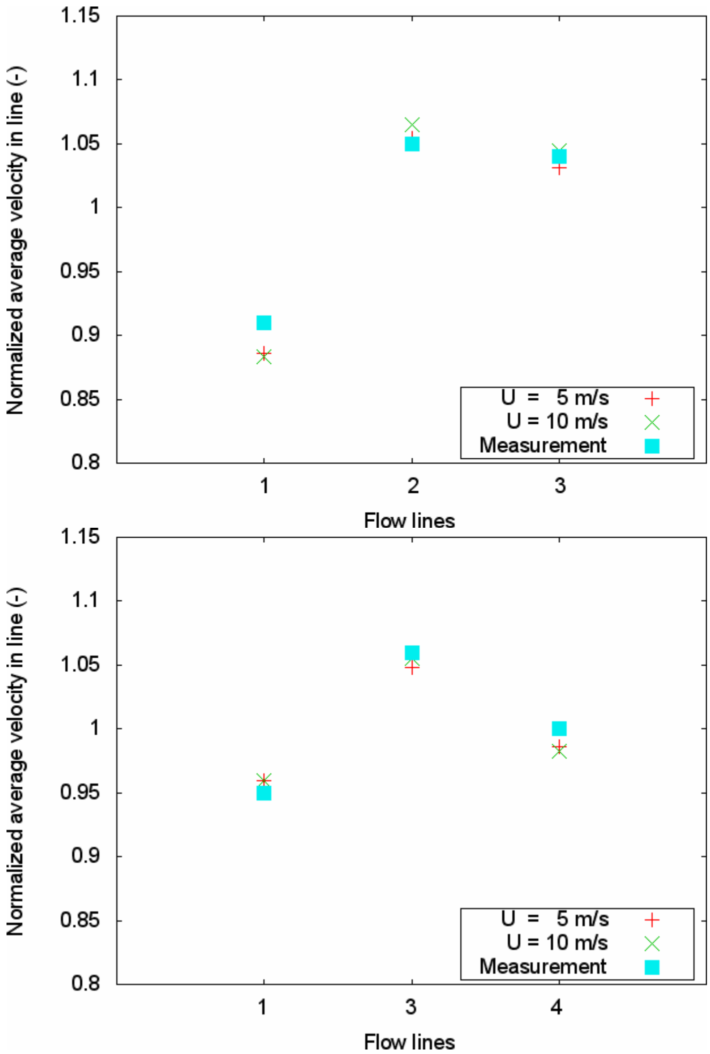

Figure 5 *CFD simulated and measured relative flow distribution over the different metering sections when 3 metering sections are in use. Flow line 1 is the first branch to the header, the other are numbered in increasing order.*

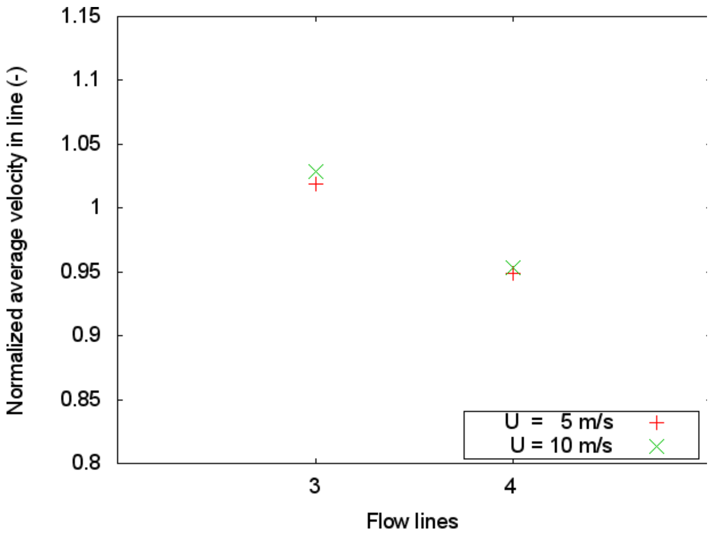

Figure 6 CFD simulated relative flow distribution over the different metering sections when 2 metering sections are in use. Flow line 1 is the first branch to the header, the other are numbered in increasing order.

5 MPU 1200 INTEGRATION ANALYSIS

As mentioned above, the average flow velocities (including the effects of the transversal flow velocity components) are calculated for each of the 6 acoustic paths of the FMC MPU 1200 ultrasonic flow meters in question. Thereafter, the integration algorithm in the MPU 1200 is applied to calculate the "measured" average axial flow velocity over the pipe cross section in the flow meters, based on the calculated average flow velocities over each of the 6 acoustic paths.

5.1 Flow Calibration

The ultrasonic flow meters are flow calibrated at Advantica before installation at Easington. Hence, the present analysis covers the deviations from the flow calibration conditions.

The flow calibration conditions are considered here as a well developed symmetric flow profile. This is modelled by the same CFD model for a long, straight pipe with the flow parameters and grid resolution as used elsewhere in this report. For this flow profile, the simulation of the MPU 1200 integration gives an over-prediction of average axial flow velocity from 0.15 – 0.17 % for Reynolds numbers in the relevant range from 10^7 to 10^{8}. This corresponds well with other work [5].

In the following part of this report, 0.15 % is therefore subtracted from the deviation from reference percentages, in order to study the deviation from flow calibration to installation at LFR Easington.

5.2 All 4 Metering Sections In Use

The ultrasonic flow meters have been installed with a straight upstream pipe length to the closest upstream bend of 54.1 diameters. The length of the spool piece is 2.4 diameters.

In the analysis, simulations have been carried out with (imagined) flow meter installations with from about 10 diameters to more than 55 diameters of straight upstream pipe, in order to study the effect of the long straight upstream pipe section. The results for this analysis are presented in Figure 7, where the deviation from reference are shown for all 4 metering sections for an inlet average flow velocity at the header of 5, 10, 15 and 20 m/s. It can be

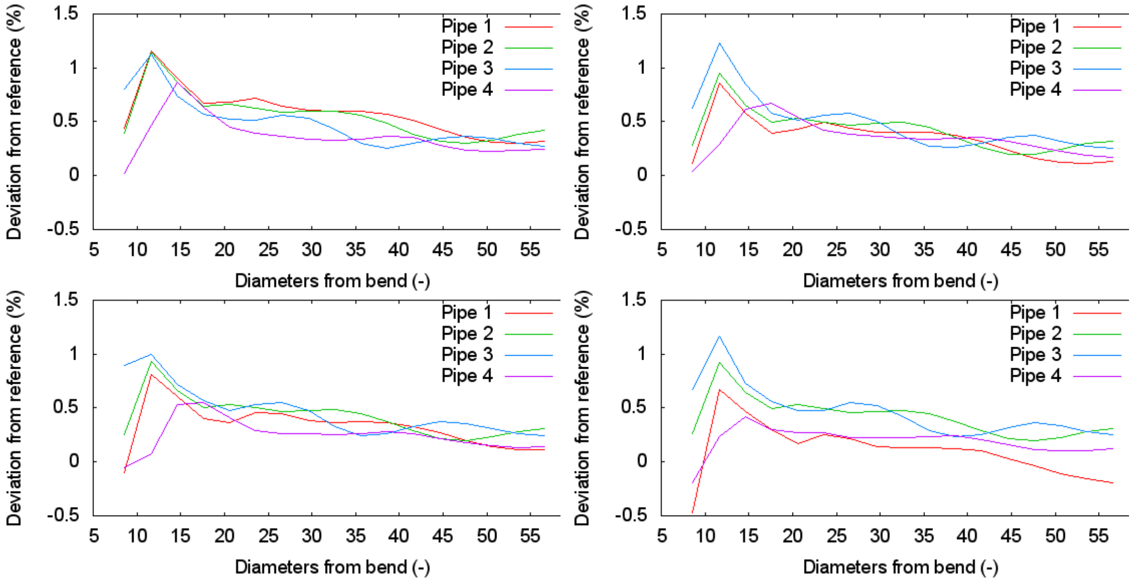

Figure 7 *Installation effect on the ultrasonic flow meters relative to the reference velocity, for imagined installations of the ultrasonic flow meters. All 4 metering sections are in use. The results are shown with an average inlet flow velocity in the header of 5 m/s (upper left), 10 m/s (upper right), 15 m/s (lower left) and 20 m/s (lower right)*

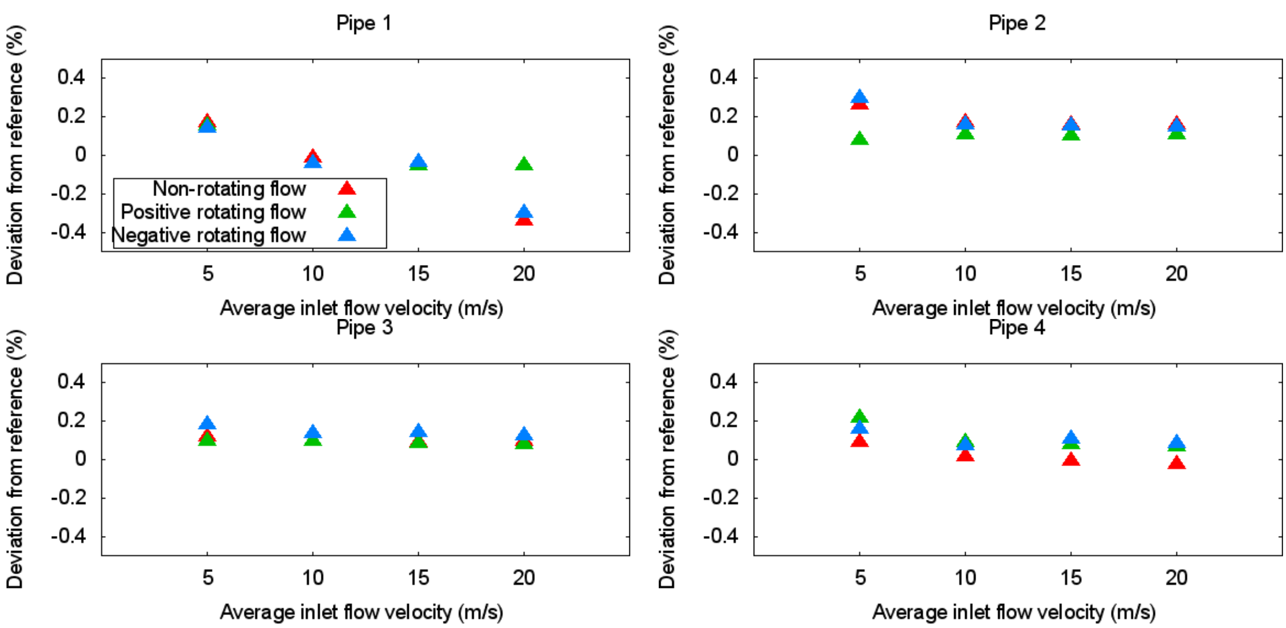

Figure 8 *Installation effect on the ultrasonic flow meters relative to the flow calibration, for the actual installation of the ultrasonic flow meters. All 4 metering sections are in use.*

seen that qualitatively, the results are quite similar over the flow velocity range. Furthermore, it is seen that if the flow meter were installed with a straight upstream pipe section of about 20 diameters or less, deviations from the flow calibration of up to 1 % could be expected due to large asymmetries in the flow profiles. At the relevant installation point of the ultrasonic flow meters, the deviation from reference is typically much less.

This is illustrated better in Figure 8, where the deviation from the flow calibration is shown as a function of average inlet flow velocity at the header. It is seen that the installation effect typically is in the order of about 0.2 % or less. All points except one are less than 0.3 %, and all points are less than 0.4 %. In the same figure, also results with swirly inlet flow profiles to the header are shown. It is seen that this does not affect the results significantly. This is expected as the T-bends branching off from the header have strong impact on the flow profiles.

5.3 2 or 3 Metering Sections In Use

Deviation from the flow calibration as a function of average inlet flow velocity at the header is shown for the two configurations with 3 metering sections in use in Figure 9 and for the configuration with 2 metering sections in use in Figure 10. The results are comparable with the results with all 4 metering sections in use.

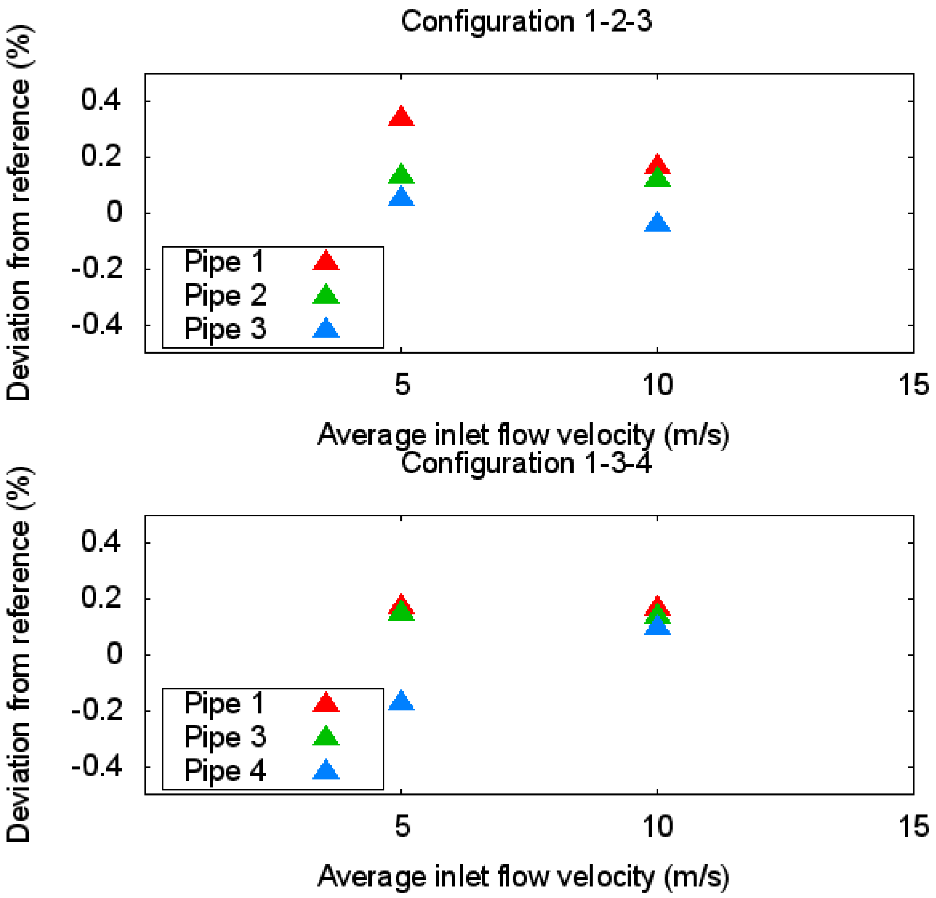

Figure 9 Installation effect on the ultrasonic flow meters relative to the flow calibration, for the actual installation of the ultrasonic flow meters. 3 metering sections are in use.

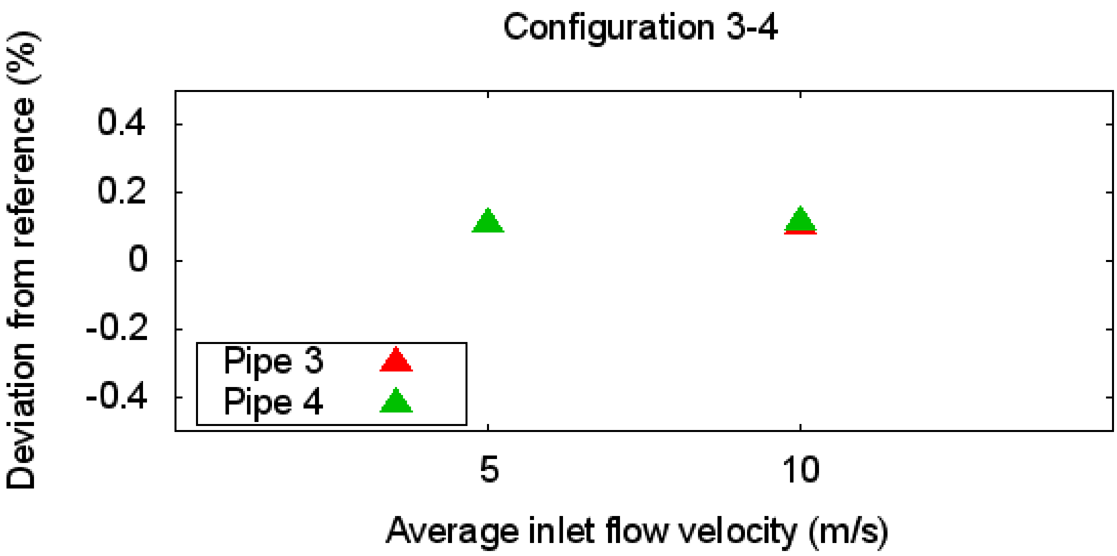

Figure 10 Installation effect on the ultrasonic flow meters relative to the flow calibration, for the actual installation of the ultrasonic flow meters. 2 metering sections are in use.

6 DISCUSSION AND CONCLUSIONS

The metering station at the Langeled Receiving Facilities in Easington consists of 4 parallel metering sections each equipped with ultrasonic flow meters. After start-up of the metering station it has been observed that the measured flow velocity profiles have been asymmetric. This has raised the question about a possible influence of the installation effect (through asymmetric flow profiles) on the measured flow rates. Based on this, the flow profiles in the metering station have been studied by CFD modelling and thereafter simulation of the ultrasonic flow meter.

The CFD analysis indicates that the flow velocity is not uniformly distributed over the 4 metering sections. This is found for all flow rates and all pipe measurement configurations (2, 3 or 4 metering sections active). In all configurations pipe 1 (the first pipe to branch off the header) has the lowest flow. Largest flow is found in pipe 3 for the 1-2-3-4 and 1-3-4 measurement configurations, and in pipe 2 in the 1-2-3 measurement configuration. With the same header flow inlet conditions the simulations predict that the relative distributions are almost independent of flow rates in the range used in the investigation.

For the configuration with all 4 metering sections in operation, the simulations have been compared with measurements for one flow rate. Generally, the simulated and measured data agree well. Largest offset is seen for metering section 1, where the simulations show a smaller relative value than the measurements, 0.83 against 0.87 for the simulations. For the other pipes the differences are smaller. Comparisons with measurements have also been carried out for the two simulated configurations with 3 active metering sections. Also here, the simulated and measured data agree well.

The simulations indicate further that the axial flow velocity profile through each of the 4 metering sections is asymmetric. It is also rotating as the gas flows downstream through the metering sections. In addition, there is a asymmetric swirly transversal flow velocity profile. This is in agreement with estimates given in literature [9], where developed flow is reached first after 64-84 ID for the Reynolds numbers used here. A swirly transversal flow is also expected because the double bend out of plane (including one T-bend) upstream each of the metering sections is traditionally found to be a strong swirl generator.

When the flow velocity profiles in the metering sections are established by CFD simulations, the effect of the asymmetric axial and transversal flow velocity profiles on the ultrasonic flow meters is analyzed by a dedicated computer program. In addition to simulation of the effect on the ultrasonic flow meters in the position where they are installed in practice, also other virtual installation locations have been analyzed. The main trend is that the deviations between the ultrasonic flow meter output and the reference are large and variable (up to about 1 %) with potential installations at the start of the straight measurement sections. With virtual installations 20-30 diameters after the bend, the deviation is smoother and decaying downstream in the pipe towards the actual meter installation. The bulk of the deviation curves are oscillatory after 20-30 diameters. This reflects the flow rotation in the pipes; the axial flow has a skew distribution in the upstream pipe section. The position of the maximum velocity in the pipe cross-section will also rotate downstream in the pipe. The flow rotation is not in phase between the different pipes. This is reflected in the oscillations in the deviation curves, which are not in phase between the pipes.

The results from the simulation of the ultrasonic flow meters have been corrected for flow calibration. The flow calibration effect has been simulated by assuming a well developed symmetric flow profile. When the correction for flow calibration has been carried out, the effect of the asymmetric flow profiles is found for all cases except one, the deviation from reference at the meter installations is less than ± 0.3 %.

7 REFERENCES

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