# Installation Effects on an Ultrasonic Flow meter

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*Abstract*-- **An ultra sonic flow meter of sing-around type for water was exposed to five experimental set-ups in front of the meter, a reference test with straight piping, a single elbow, a double elbow out of plane, a reduction in pipe diameter and a pulsating flow test. All tests were performed in a flow calibration facility and in the flow range, stated as Reynolds number in the meter, approximately from 25 to 110.000.**

**The measurements with the four installation effects were ' pared with the first reference test and the percentage e.. or was calculated.**

1. **The single elbow caused errors with up to 3 per cent. This largest error showed up at Reynolds number 4000. In most of the flow range there were no or smaller errors.**
2. **The errors generated by the double elbow were slightly arger than those caused by the single elbow. The maximum error occurred at Reynolds number 4000 and was about 4 per cent.**
3. **The diameter reduction only gave rise to clear errors at high flow rates with Reynolds number over 100.000. The largest error was 2 per cent.**
4. **The pulsating flow generated errors only at Reynolds number lower than 20.000. The errors were mainly in the range of 1 - 2 per cent but at Reynolds number below 300 the magnitudes of the errors were as high as 80 per cent.**

**The results demonstrate that all of the installation effects tested introduce errors in the flow measurements. This could perhaps be explained by disturbed flow profiles, triggering of turbulence and for the pulsating flow flattening of the flow profile. The errors occurred mainly in the flow ranges where the calibration curve showed marked slopes.**

## I. INTRODUCTION

,project concerning measurement quality assurance in district heating systems is in progress at Luleå University of Technology. The district heating industry desires accurate heat measurements. The flow measurement involved can be effected by different installation effects. : scope of the project is to examine the possibility of self diagnostic flow meters. For this reason experimental work concerning installation effects has been performed.

Installation effects are regarded as one of the most serious origin of errors in flow measurements. All commonly used flow meter types are to different degrees effected by installation effects. An example is [1]. Ultrasonic flow meters are also effected by different flow disturbances. It has been shown, both with experimental work and simulations, that single and double elbows in front of an ultrasonic flow meter will cause errors [2] [3] [4] [5] [6]. Further it has been demonstrated that pulsating flow will give rise to errors [7] [8].

Previous work considered both static installation effects as pipe bends and dynamic effects as pumps [8]. The experimental work presented in this paper is a continuation of that work. The ultrasonic flow meter tested now is a new improved meter with higher sampling rate and better precision. Further the test facility where the experiments were carried out provided an increased flow range, both lower and higher flow rates. The frequency of the pulsation generated in these new experiments is lower, more imitating a fast control valve than a pump.

This paper investigates errors introduced to an ultrasonic flow meter for water by five different experimental configurations, one reference experiment with a long straight pipe in front of the meter and four disturbances. The disturbances that were mounted in front of the meter were, a single elbow, a double elbow out of plane, a reduction in pipe diameter and a rotating valve generating a pulsating flow. The experiments were performed in a flow meter calibration facility and in the flow range with Reynolds number approximately from 25 to 110.000 in the 10 mm diameter flow meter.

## II. THE EXPERIMENTS

The experiments are intended to imitate flow meter installations that could be found in for example district heating systems, fresh water distribution systems and small process systems. In these systems pipe bends, pumps and fast control valves could be found fairly close to the meter. The flow range tested was from close to zero flow to slightly less than 2 m/s in 25.6 mm piping. This flow range is believed to be relevant in the systems mentioned above.

The tested ultrasonic flow meter was exposed for five different experimental set-ups:

1. Straight piping with a length of 110 pipe diameters (D) was mounted in front of the meter. This worked as a reference experiment.
2. A single elbow was mounted 11 D in front of the meter.
3. A double elbow out of plane was mounted 11 D in front of the meter.
4. A diameter reduction from 51.2 to 25.6 mm piping was mounted 13 D in front of the meter.
5. By rotating a butterfly valve with 130 rpm a 4.4 Hz pulsation was added to the flow.

Each of the experimental set-ups will be more carefully described in the following text in connection with the presentation of the results. The flow meter is described below. Also the calibration facility in witch the experiments were performed is described below.

### A. *The ultra sonic flow meter*

The flow meter under testing was an ultra sonic flow meter of sing-around type for water. The geometric design of the flow meter is described in figure 1.

This small ultrasonic flow meter has a diagonal sound path tilted 20° compared with the pipe centre line. The distance between the two transducers is 59.5 mm. The diameters of the sound path and the pipe are both 10 mm. Therefor the ratio between the sound path diameter and pipe diameter equals one. The diameter of the meter was reduced in order to increase the flow velocity through the meter. An initial 19 mm bore diameter is reduced by a 10° cone shaped section to 10 mm. The 25.6 mm diameter piping of the test facility is connected to the meter body by thread fittings.

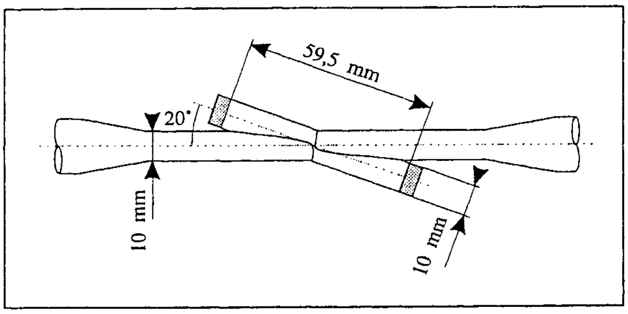


**Figure 1:** The schematic geometric design of the ultrasonic flow meter.

The meter transmitted 150 sound pulses in one direction. The mean time for the travelling of the sound pulse between the transducers was then communicated to a host computer. The meter then transmitted another 150 sound pulses in the other direction and then again communicated the mean travelling time. This procedure was continuously carried out during the measurement. After a measurement series was completed, the host computer calculated the flow rates off line. This arrangement was chosen in order to get a higher sampling frequency of the flow meter. The sampling frequency achieved was 112 Hz. Each measurement lasted 120 seconds. This means that each of the points in the plots presented below consists of a little more than 13000 averaged measurements. The principle of operation of the flow meter and the algorithms used to calculate the flow velocities are described in [9].

The tested flow range corresponds to about 2.5 mm/s and 11 m/s in the 10 mm diameter pipe in the flow meter or stated as Reynolds number from about 25 to 110.000. In the tested flow range 73 measurements at different flow rates were performed. The reference experiment was repeated six times and the other experiments three times. During all of the experiments the temperature of the water varied within 19 ±1.5°C and corresponds to a change in density of less than ±0.04 per cent.

*B. The flow meter calibration facility*

The tests were performed in a flow meter calibration facility recently built at Luleå University of Technology. The calibration facility is shown in figure 2. This facility is a development of a previous one outlined in [10].

The flow is generated by the head tank and controlled by three control valves. It's possible to produce a pulsation in the flow by using a rotating butterfly valve. In one of the three 10 m long test runs the experiments were set up. Finally the water was collected in one of the three tanks and weighed. The capacities of the scales are 25, 180 and 1200 kg. By using three scales the flow range of the calibration facility was increased. The test range is from about 1 dm³/h to approximately 40 m³/h. Normally the diameter of the piping is 51.2 mm but during these experiments is was 25.6 mm.

The calibration facility is based on continuous weighing. The estimated accuracy is better than ±0.2 per cent. In these experiments the absolute accuracy is however of little interest as only the change compared to the reference experiment, and not to some "true" flow, is considered.

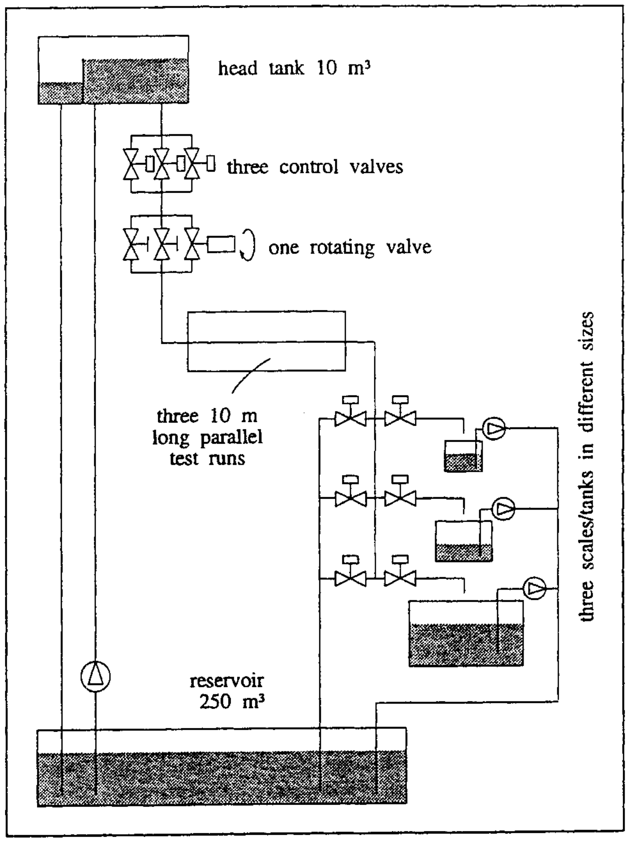


**Figure 2:** The general outline of the flow meter calibration facility.

The function of the facility is controlled by a computer. This computer also collects the data and calculates the flow rate. It also communicates with the host computer of the ultrasonic flow meter.

## III. RESULTS

The results are mainly presented in two different ways by using the *k-factor* and the *error*. The calibration factor, *k-factor*, is defined as the ratio between the flow velocity determined by the calibration facility and the one measured by the flow meter.

$$k-factor = \frac{v_{calibration}}{v_{ultrasonic}} \qquad (1)$$

The mean *k-factor* of the six reference experiments was multiplied with the flow measurements made by the flow meter to obtain compensated measurements. The results from the following experiments are presented as the percentage error, denoted *error*, compared with the reference experiment.

$$error = \frac{v - mean(v_{ref})}{mean(v_{ref})} * 100 \qquad (2)$$

Here $v$ and $mean(v_{ref})$ denotes the compensated velocity for each point in the measuring sequence and the compensated mean velocity of the reference experiment. If the flow meter overestimates the flow compared with the reference experiment, it will show as a positive error. An underestimation will appear as a negative error.

### A. *The reference experiment*

The reference experiments work as base line results. The other experiments with disturbances will be compared with this reference case. The set-up is shown in figure 3.

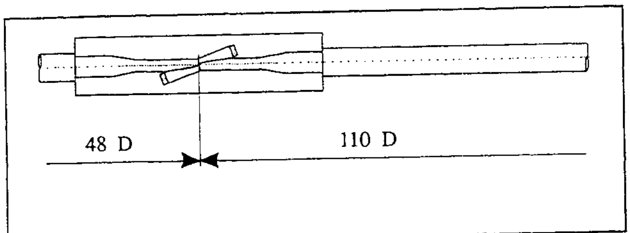


**Figure 3:** Top view of the experimental set-up for the reference experiment. The flow enters the meter from the right.

The diameter of the piping in front and after the meter (D) is 25.6 mm. In the reference experiment only straight piping was mounted, 110 D in front of the meter and 48 D behind. The 110 D before the meter was used to ensure a fully developed flow profile at the entrance of the meter. In figure 4 a plot of the calibration data for the undisturbed reference experiment is presented. Each point in the plot is a mean of the six sequences.

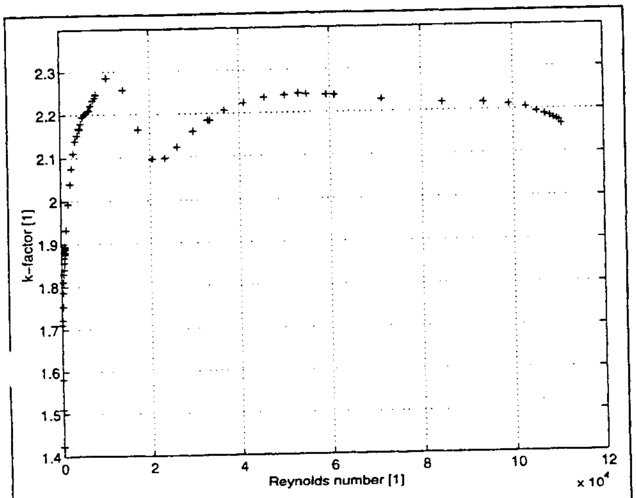


**Figure 4:** The mean reference calibration curve of the six measuring sequences.

Reynolds number in figure 4 and in the following plots is based on the flow determination made by the calibration facility and the 10 mm diameter of the flow meter.

Most of the curve represents a k-factor of about 2.2. The main reason for the curve not equalling 1 is to be found in the geometric design of the meter. The sound beam only interacts with the flow slightly less than half the way between the transducers.

The two bumps in the calibration curve at Reynolds number 10.000 and 20.000 are probably the result of the cavities near the transducers and the fittings and reduction in diameter.

The compensated mean reference velocity is subsequently subtracted accordingly to equation 2 so that the deviation in velocity is displayed in percentage. Figure 5 shows the error of the six measurements made with the reference set-up compared with the mean.

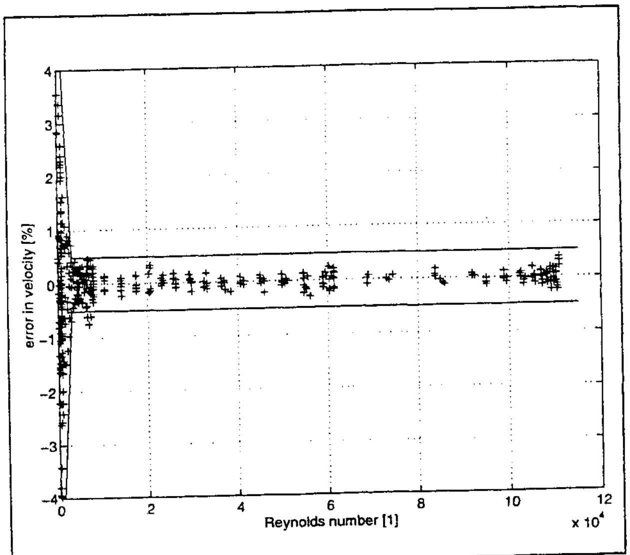


**Figure 5:** The percentage error in the six reference measuring sequences. The solid lines represent the limits confining the six reference measurements with a 95 per cent confidence level.

In figure 5 and the following plots the solid curves indicate the limits confining the data from the six measurements made with a 95 per cent confidence.

### B. *The single elbow experiment*

The first installation disturbance tested was the single elbow. The set-up is shown in figure 6.

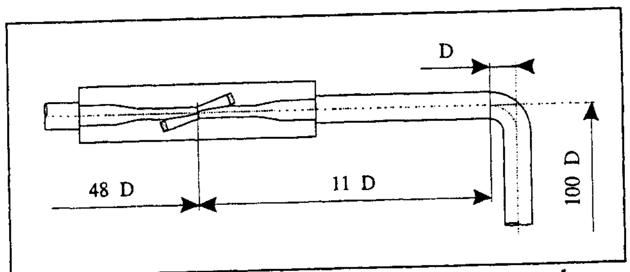


**Figure 6:** Top view of the experimental set-up for the single elbow experiment. The flow enters the meter from the right.

There was 11 D of straight piping between the meter and the outlet of the elbow. In front of the elbow a 100 D long straight pipe ensured a fully developed flow profile before the elbow. The bending radius of the elbow equalled the pipe diameter. The angular orientation of the elbow was such that the transducer plane coincided with the elbow plane.

In figure 7 a plot of the error in the measured velocity for the single elbow experiment is presented. In figure 7 and in the following plots (+) marks the first measuring sequence, (o) the second and (x) the third.

The single elbow causes both over and under estimations in the flow measurements. Below Reynolds number of 10.000 the flow rate is underestimated by a little less than 3 per cent. Between 10.000 and 20.000 the flow is instead overestimated by about 1 per cent. With increasing Reynolds number up to 30.000 the flow is again underestimated this time by approximately 1 per cent. Finally at very high flow rates, with Reynolds number greater than

100.000, the flow rate is overestimated by a little less than 1.5 per cent.

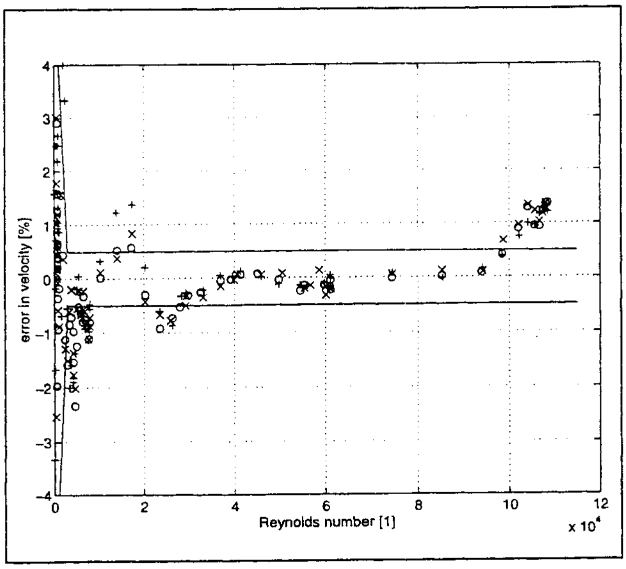


**Figure 7:** The percentage error due to the single elbow. The solid lines represent the limits confining the six reference measurements with a 95 per cent confidence level.

Except for the range between 10.000 and 20.000 in Reynolds number all three of the measurement series show the errors stated above. Even when the meter is disturbed by the single elbow the repeatability seems to be the same as for the reference case. Figure 8 presents in a zoomed plot the errors at low Reynolds number. There are no errors observed for Reynolds numbers lower than 2000.

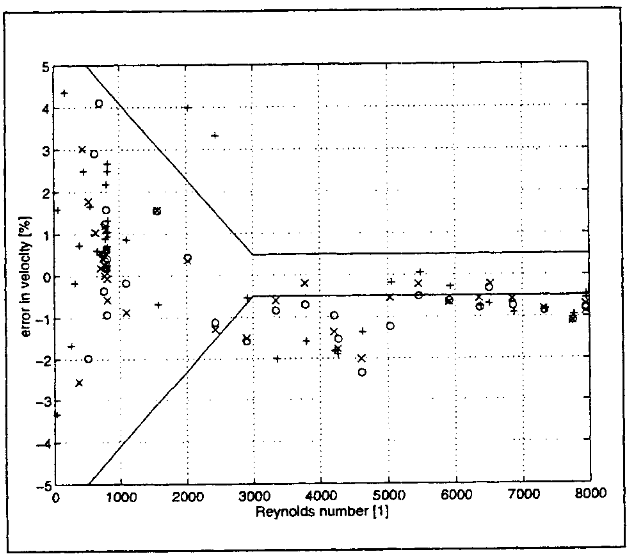


**Figure 8:** The percentage error due to the single elbow. The solid lines represent the limits confining the six reference measurements with a 95 per cent confidence level.

The shift in the calibration curve could perhaps be explained by the disturbed flow profile and the triggering of turbulence at lower Reynolds numbers [8]. If adding turbulence to the reference case the data in figure 4 would move left as turbulent behaviour would appear at lower Reynolds numbers. This could explain that the errors in figure 7 arise at Reynolds numbers where the calibration curve in figure 4 shows a marked slope. With the single elbow the flow is underestimated when the slope is positive and underestimated when the slope is negative.

*C. The double elbow experiment*

The second installation disturbance tested was the double elbow. The set-up is shown in figure 9.

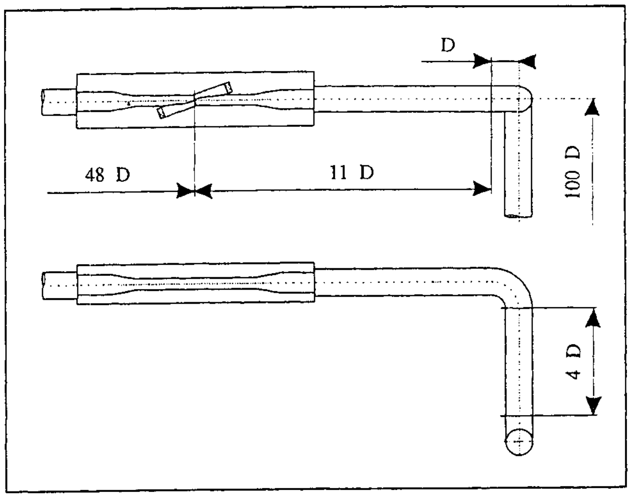


**Figure 9:** Top view (top) and side view (bottom) of the experimental set-up for the double elbow experiment. The flow enters the meter from the right.

Between the meter and the outlet of the second elbow there was 11 D of straight piping. In front of the first elbow a 100 D long straight pipe again ensured a fully developed flow profile before the elbow. The bending radius of both elbows were the same as in the single elbow experiment. The angular orientation of the elbows was such that the angle between the transducer plane and the plane of the elbow closest to the meter was 90°. The two elbows were spaced with 4 D. Because of the distance between the elbows the flow after the second elbow probably swirled only gently [1]. In figure 10 a plot of the error in velocity for the double elbow experiment is presented.

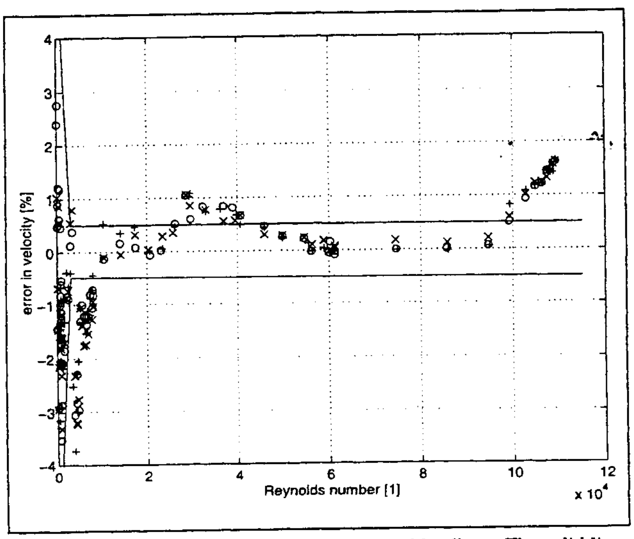


**Figure 10:** The percentage error due to the double elbow. The solid lines represent the limits confining the six reference measurements with a 95 per cent confidence level.

The experiment with the double elbow causes, as in the single elbow case, both over and under estimations in the flow measurements. Below Reynolds number 10.000 the results look about the same as for the single elbow but the errors are increased some. The flow is at most underestimated by a little less than 4 per cent. Between Reynolds number 10.000 and 30.000 the measurements are mainly within the ±0.5 per cent range marking the spread in the reference experiment. In the range of Reynolds numbers from 30.000 to 40.000 the flow is overestimated by about 1 per cent. In this range the single elbow measurements show no error. Again at Reynolds number greater than 100.000, the flow is overestimated by more than 1 per cent. Figure 11 displays the error at lower flow rates.

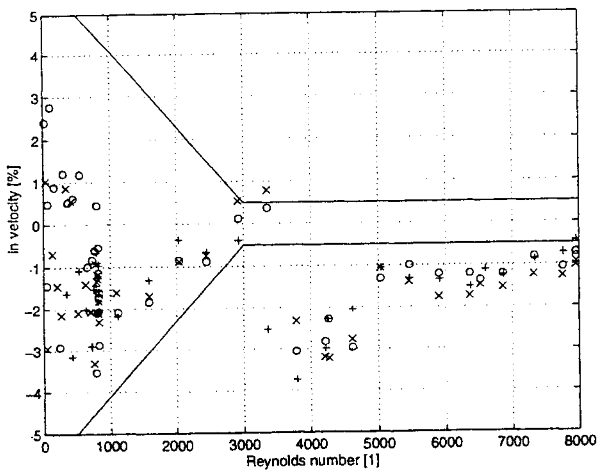


**Figure 11:** The percentage error due to the double elbow. The solid lines represent the limits confining the six reference measurements with a 95 per cent confidence level.

Compared with the single elbow experiment the errors now show up at higher Reynolds number. The first error occurs approximately at Reynolds number 3000 and has a magnitude of about 4 per cent. All three of the measurement series show the errors stated above. Also disturbed by the double elbow the repeatability of the meter seems to be almost the same as in the reference experiment.

The most clear difference between the single and double elbow experiments appears in the flow range with Reynolds numbers from 10.000 to 40.000. The double elbow set-up was changed compared with the single elbow the way that the elbow closest to the elbow was tilted 90°. Earlier investigations on ultrasonic gas flow meters show that the behaviour of the meter can shift when the angular orientation of the elbow is changed [4]. Perhaps this could be an explanation or part of an explanation of shift in error curves. Likely the flow profile and the swirl were also changed.

*D. The diameter reduction experiment*

The third installation disturbance tested was the reduction in diameter. The set-up is shown in figure 12. The diameter of the piping in front of the meter was reduced by using a 45° cone shaped pipe segment. The diameter of the pipe before the reduction was 2 D (51.2 mm) and after 1 D (25.6 mm). Between the meter and the outlet of the cone 13 D of straight piping was mounted.

In figure 13 a plot of the error in velocity for the diameter reduction experiment is presented. The errors caused by the reduction in diameter are smaller, except at the highest flows, than those caused by the single and double elbow. In the flow range with Reynolds number higher than 20.000 the flow seems to be overestimated but clear errors are only generated for Reynolds number higher than 100.000.

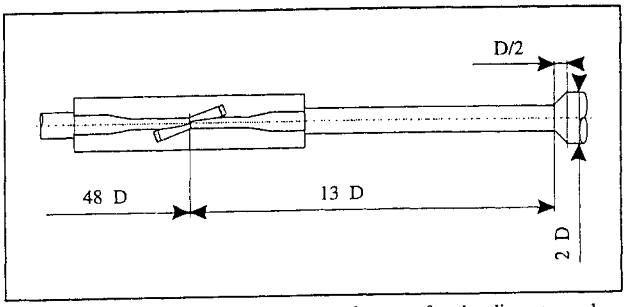


**Figure 12:** Top view of the experimental set-up for the diameter reduction experiment. The flow enters the meter from the right.

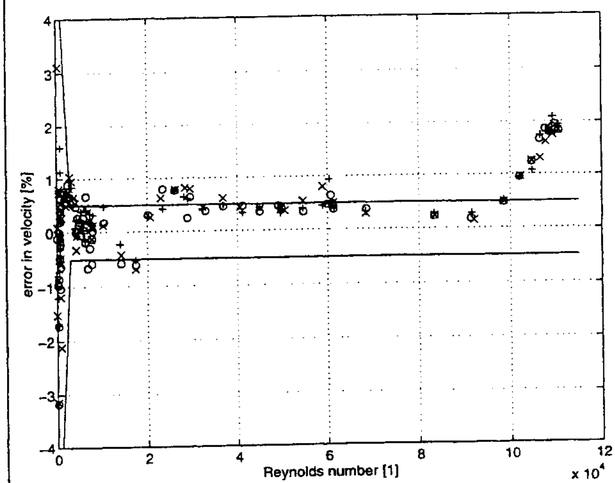


**Figure 13:** The percentage error due to the reduction in diameter. The solid lines represent the limits confining the six reference measurements with a 95 per cent confidence level.

The flow is here overestimated by 2 per cent. Below Reynolds number of 20.000 the flow is both over and underestimated by about 1 per cent. No errors occur at Reynolds number lower than 3000. The repeatability of the meter seems again to be close to the one in the reference case.

*E. The pulsating flow experiment*

The fourth disturbance tested was a dynamic installation effect, the pulsating flow. The set-up around the meter was the same as in the reference experiment presented in figure 3. A rotating valve mounted 175 D in front of the meter, 110 25.6 mm and 65 51.2 mm diameters, opened and closed the flow path a little more than four times a second. At high flows this arrangement caused vibrations in the piping. Therefor a bypass valve was slightly opened at high flows to reduce vibrations.

In figure 14 a plot of the error in velocity for the 4.4 Hz pulsating flow experiment is presented. The (+), (o) and (x) mark the data obtained with the bypass valve closed and the (*) marks the data when this valve was partly opened. All measurements with the valve slightly opened are within the limits representing the uncertainty of the reference experiment. At Reynolds number over 20.000 actually all the measurements are within these limits. In the flow range below Reynolds number 20.000 the flow is both over and underestimated by 1 to 2 per cent. As can be seen in figure 15, the meter underestimates the flow with tenths of per cent for very small flows with a few hundred in Reynolds number.

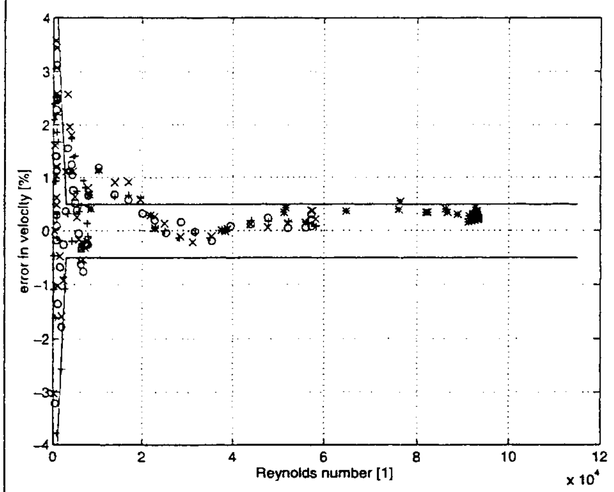


**Figure 14:** The percentage error due to the 4.4 Hz pulsation. The solid lines represent the limits confining the six reference measurements with a 95 per cent confidence level.

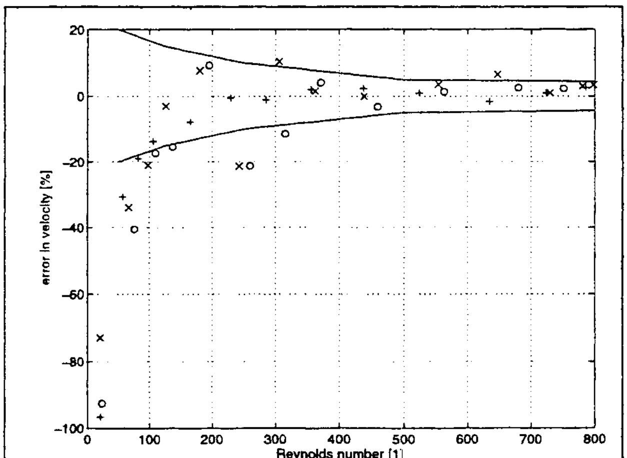


**Figure 15:** The percentage error due to the 4.4 Hz pulsation. The solid lines represent the limits confining the six reference measurements with a 95 per cent confidence level.

Here no swirl is present in the flow neither is the flow profile asymmetric. A pulsating flow will cause other effects. At laminar and transient flow the mean flow profile is generally flattened out when a pulsation is present in the flow. This shows as an imaginary high Reynolds number. An ultrasonic flow meter then normally underestimates the flow. A pulsation in fully developed turbulent flows is not likely to effect the performance of the meter. [7]

The measurements with pulsating flow show good consistency with previous results. Aliasing is believed to have little influence on the error as the sampling frequency is about 30 times higher than the pulsation frequency.

## IV. DISCUSSION

The results demonstrate that all installation effects tested give rise to errors in the flow measurements of 2 per cent or more compared with the reference experiment. The flow rates were both over and underestimated. These errors occurred mainly in the flow ranges where the calibration curve showed marked slopes. This was in the ranges with Reynolds number 25 - 40.000 and 100.000 - 110.000.

1. For Reynolds number 3000 and higher the six reference measurements were confined within a ±0.5 per cent limit with a 95 per cent confidence level.
2. In the single elbow experiment the errors caused were up to 3 per cent in the range of Reynolds number from 3000 to 5000. At Reynolds number higher than 100.000 errors of about 1.5 per cent also occurred. In most of the flow range there were no or smaller errors.
3. The errors generated by the double elbow were similar to those caused by the single elbow. The errors were however slightly larger. The maximum error was a little less than 4 per cent and showed up at Reynolds number 4000.
4. In the diameter reduction experiment the clear errors took place at Reynolds number higher than 100.000. The largest error was approximately 2 per cent.
5. The pulsating flow generated no errors at Reynolds number higher than 20.000. In these fully developed turbulent flows the pulsation did not effect the performance of the meter. At Reynolds number lower than 20.000 errors showed up mainly in the range of 1 to 2 per cent. At Reynolds number below 300 the errors were as large as 80 per cent.

A future paper will investigate if the spread in data could be used to detect the installation effects presented in this paper. If so, perhaps a measure of the scattering could be used for a self diagnostic flow meter.

## V. ACKNOWLEDGEMENTS

This project is financed under a grant from the Swedish District Heating Association.

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