Upstream pipe wall roughness influence on ultrasonic flow measurement

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Abstract

In high-pressure natural gas pipelines, installation requirements of modern ultrasonic flow meters usually only specify an upstream pipe length, without mentioning wall roughness. Since no data were available to support a specification, Measurement Canada and TransCanada PipeLines decided to conduct a series of tests under well-defined conditions. This document reports the results. The tests were carried out at the Ruhrgas test facility Pigsar in Germany, where two 12» Q.Sonic® 3-path ultrasonic flow meters (Instromet®) were repeatedly calibrated at about 45 bar, while various pipes of different roughness were mounted upstream. Two Ruhrgas engineers measured the wall roughness of the pipes using ISO 9001 certified standard methods. Over the range of conditions investigated, an increase of the roughness R_a from about 5 µm to probably 20 µm appears to increase the meter reading by about 0.1 - 0.2 %.

1 Introduction

In high-pressure natural gas pipelines, installation requirements of modern ultrasonic flow meters usually only specify an upstream pipe length, without mentioning wall roughness. The reason for this requirement is to make sure, at least to some extent, that the flow meter is presented with a reasonably well-behaved velocity profile. The velocity profile, however, not only depends on upstream conditions and Reynolds number, but on wall roughness also. Since no data were available to support a specification for wall roughness, Measurement Canada and TransCanada PipeLines decided to conduct a series of tests under well-defined conditions. Two 12» Q.Sonic® 3-path ultrasonic flow meters (Instromet®) were repeatedly calibrated at about 45 bar, while various pipes of known and different roughness were mounted upstream. This paper presents the results. Its outline is as follows: In chapter 2 the concept of wall roughness will be discussed, its various measures will be explained, and its influence on the velocity profile. The next chapter will present the main results of the roughness measurements on the pipes used in the tests. The details are described in an official Ruhrgas report (in German). Chapter 4 contains the results of the flow calibrations at the Pigsar facility. Finally the results are summarized in a conclusion.

2 Roughness

Every practical surface of a solid state material is like a microscopic landscape, with mountains and valleys. It has a finite roughness: only mathematical surfaces are perfectly smooth. The surface of even the best straight pipe is not an exact mathematical cylinder, the cylinder is just an approximate description of its shape. The roughness is part of the difference between the real shape and the ideal one. The roughness results not only from the internal structure of the material, its atomic or molecular nature, but from the processes that created and influenced the surface, such as machining, polishing, coating, corrosion and the like. Various measures exist to characterize the microscopic landscape, each is a particular compromise between local and more global features of the surface. The most widely used are R_a.and R_z. The first is defined as the arithmetical mean of the absolute values of the profile departures within the measuring length L. shows an illustration.

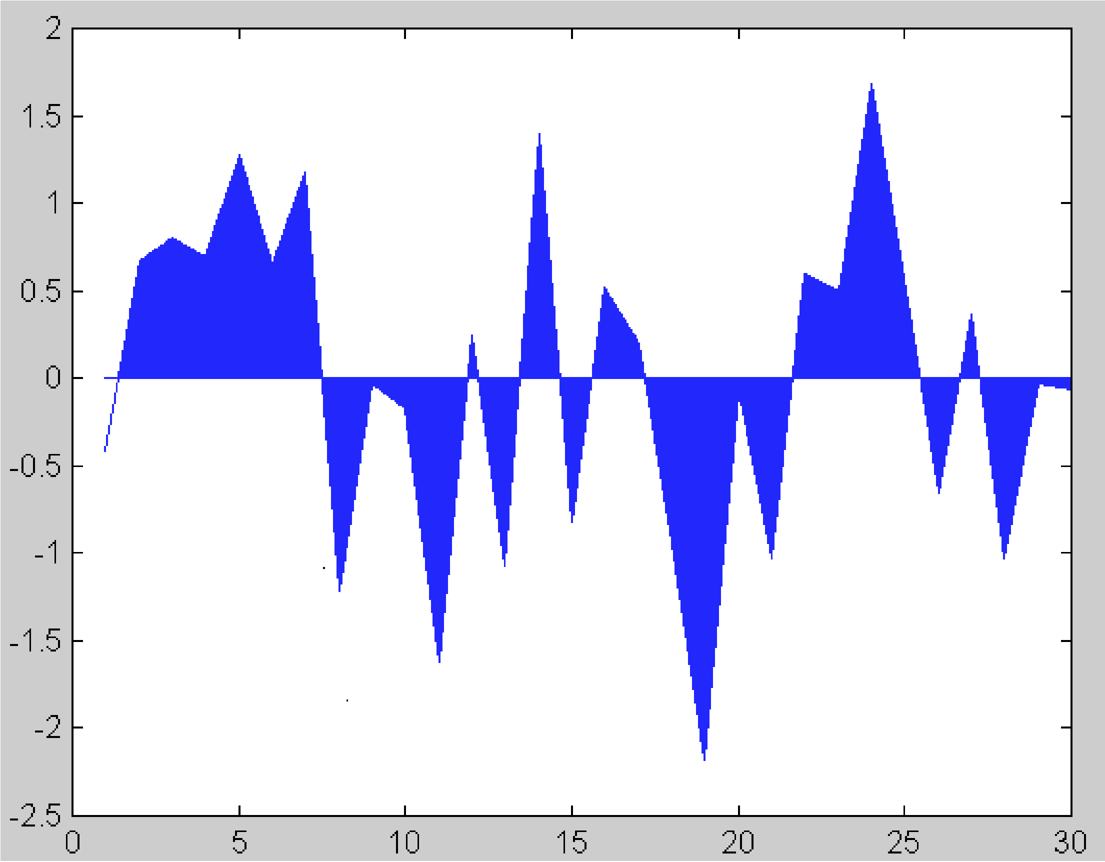

Figure 1, Definition of Ra

R_z is defined as the average value of the absolute values of the heights of five highest profile peaks and the depths of five deepest profile valleys within the measuring length

$$R_a = \frac{1}{L}\int_0^L \left| y(x) \right| dx \tag{1}$$

$$R_z = \frac{1}{5}\sum_{i=1}^{5}\left\{\left|y_i^+\right|+\left|y_i^-\right|\right\} \tag{2}$$

where yI+ denotes the highest peaks and yI- the deepest valleys on the measuring interval. illustrates this definition

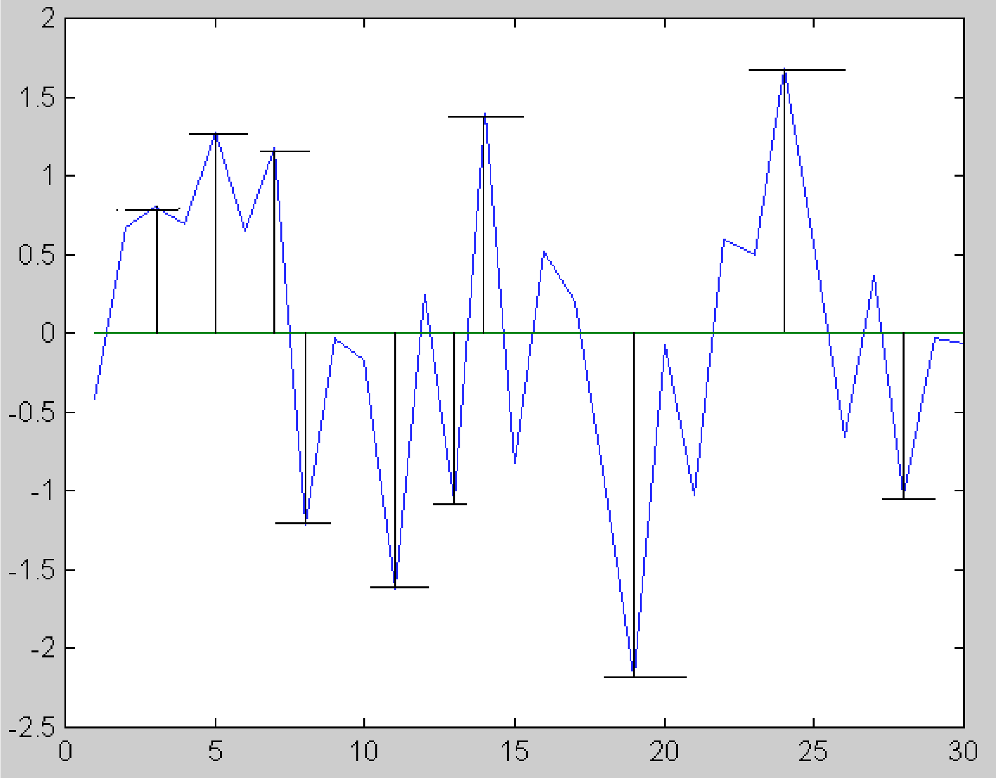

Figure 2, Definition of Rz

In many practical situations the value of R_z appears to be about five times that of Ra. According to Van der Kam (1993) in new gas pipes R_a (5 µm, whereas in old pipes it may increase to about 30 µm.

In swirl-free flow through long straight cylindrical tubes with radius R, the only non-zero time-averaged velocity component will be in the axial direction, and it will be a function of radial position r / R only. According to Schlichting(1968) the semi-empirical relation

$$v(r) = v_{max}\left(1-\frac{r}{R}\right)^{\frac{1}{n}} \tag{3}$$

approximately describes this function, which is usually called the fully developed velocity profile. In this relation n, and therefore the velocity profile v(r), is a function of the Reynolds number R_e and the pipe roughness. Colebrook (1939) uses the concept of ‘equivalent sand roughness’ rather than R_a or R_z, probably because the latter were not yet defined at that time. If we equate R_a with his ‘equivalent sand roughness’ Colebrook’s implicit relation for n can be written as

$$n = 1.74 - 2 \log_{10}\left(\frac{Ra}{R} + 18.57\frac{n}{Re}\right) \tag{4}$$

Note that roughness relative to pipe radius rather than roughness proper is the determining factor. As an example, for a 12» pipe the following table lists the value of n for two values of R_a and Reynolds number

	Re = 1 M	Re = 10 M
Ra = 5 µm	9.13	10.3
Ra = 30 µm	8.63	9.07

Figure 3 shows that a smaller value of n indicates a more peaked velocity profile; a higher value flattens the profile. This change of the velocity profile could conceivably influence the reading of an ultrasonic flow meter, which is the reason for the investigation reported here.

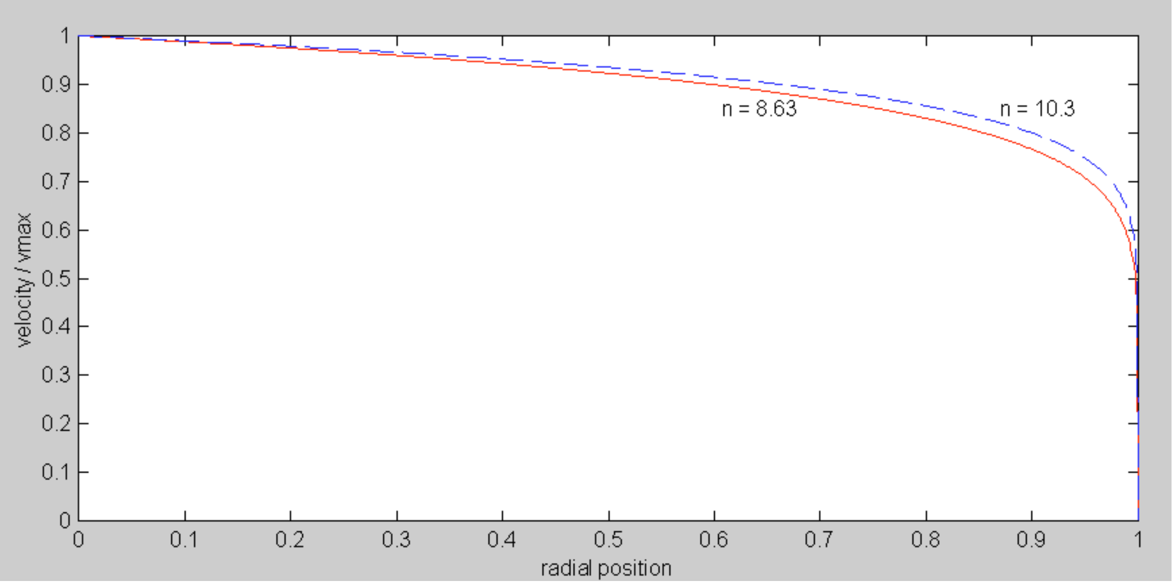

Figure 3, Velocity profile as a function of n

3 Roughness Measurements

The inner wall roughness of four 12» pipes was measured using the stylus method, which uses a mechanical pick-up (Hommel, type T500) moving at constant speed across the surface. A linear voltage differential transformer (LVDT) generates an electrical signal that corresponds to the shape of the surface, like a magneto-dynamic cartridge of a gramophone record player. The measuring range is 160 µm (+60/-100 µm). A measuring length of 15 mm was chosen, and a cut-off length of 2.5 mm. The purpose of the cut-off length is to eliminate unwanted components from the signal. Apart from R_a and R_z two other quantities were determined: Rmax which is the depth between the highest peak and the deepest valley, and Rk which measures the middle part of the roughness distribution and does not look at the highest peaks or deepest valleys. Rk is illustrated in the next figure, taken from DIN 4776.

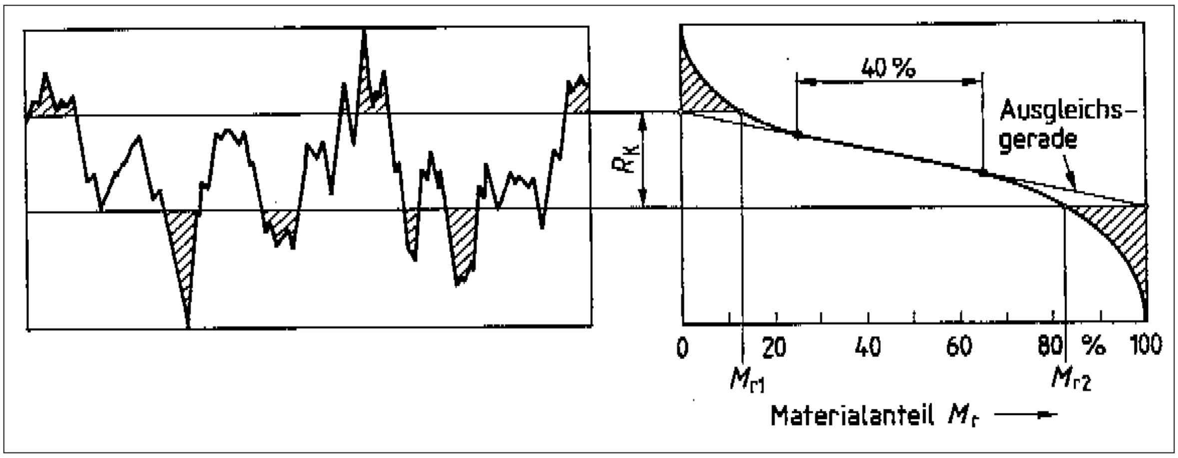

Figure 4, Definition of Rk

The engineers who conducted the measurements were J. Laimmer and E. Reinhard, both from the Ruhrgas research laboratory TBZQ-Metallkunde, and specialists in roughness measurement. The laboratory is ISO 9001 certified, the measurements were carried out according to DIN standards 4768 and 4776. The roughness tests were labeled 1974.1 through 1974.4 and they were all done at the Ruhrgas test facility Pigsar in Dorsten, Germany.

Daniel Industries Canada manufactured the pipe used in test nr 1974.1 on April 29, 1998, and labeled it DCM 98 - 529. The length of the pipe is about 3.1 m and its inner diameter equals 303 mm. On May 7, 1998 its inner wall roughness was measured at 24 positions along the pipe, these tests were witnessed by the author of this report. Visual inspection showed the distribution of the roughness to be regular over the circumference of the pipe, so all 24 test positions were taken on the bottom of the pipe, documented as 600 (6 o'clock). R_a was found as 5.1 ± 1.6 µm mean and standard deviation, whereas for R_z a value of 33.3 ± 9.6 µm was obtained. R_m is 45.6 ±13.7 µm and Rk is 14.9 ± 6.2 µm. Figure 5 shows the data.

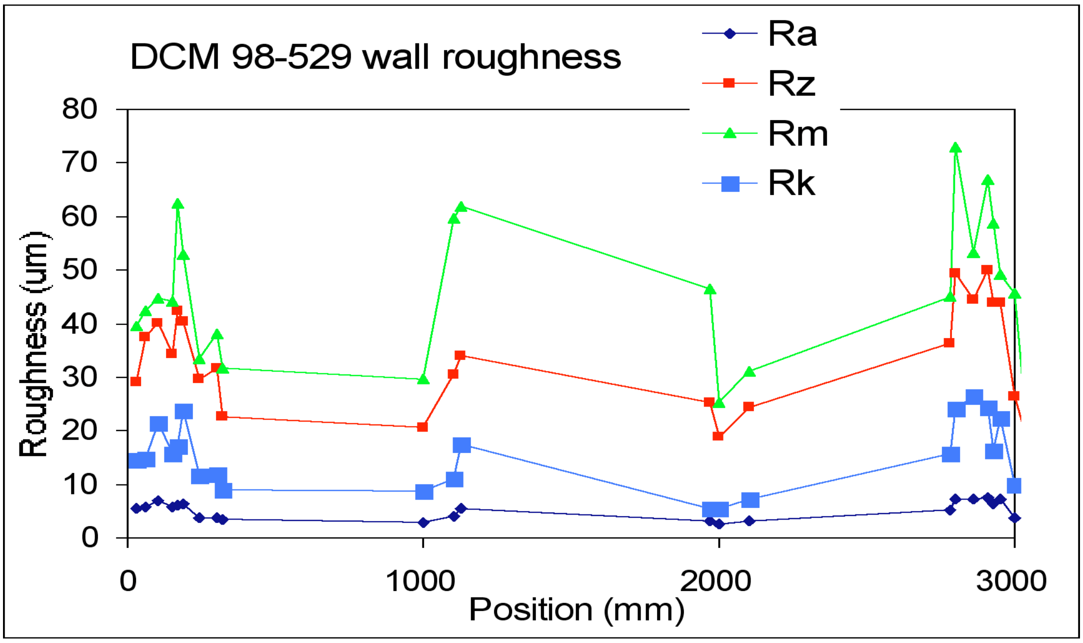

Figure 5, Wall roughness of pipe DCM 98-529

The pipe in test nr 1974.2 was manufactured by Daniel on June 15, 1998, and labeled DCM 98 - 636. It has similar dimensions as DCM 98 - 529. On August 28, 1998 its inner wall roughness was measured at 16 points along the pipe, all at 6 o'clock position. R_a was found as 5.2 ± 2.3 µm mean and standard deviation, whereas for R_z a value of 36.6 ± 13.2 µm was obtained. Figure 6 shows the data. It is clear that the two Daniel pipes have about equal roughness. A further observation is that for these pipes the standard deviations of R_a and R_z are about 30 to 40 % of their mean values, respectively. Figures 5 and 6 are graphical representations of tables 1974.1 and 1974.2 in the Ruhrgas report (Laimmer and Reinhard, 1998). As expected there is a good correlation between the various roughness measures. The next figure shows the scatter diagram of R_z versus Ra, the correlation coefficient is about 0.9 for the two DCM pipes.

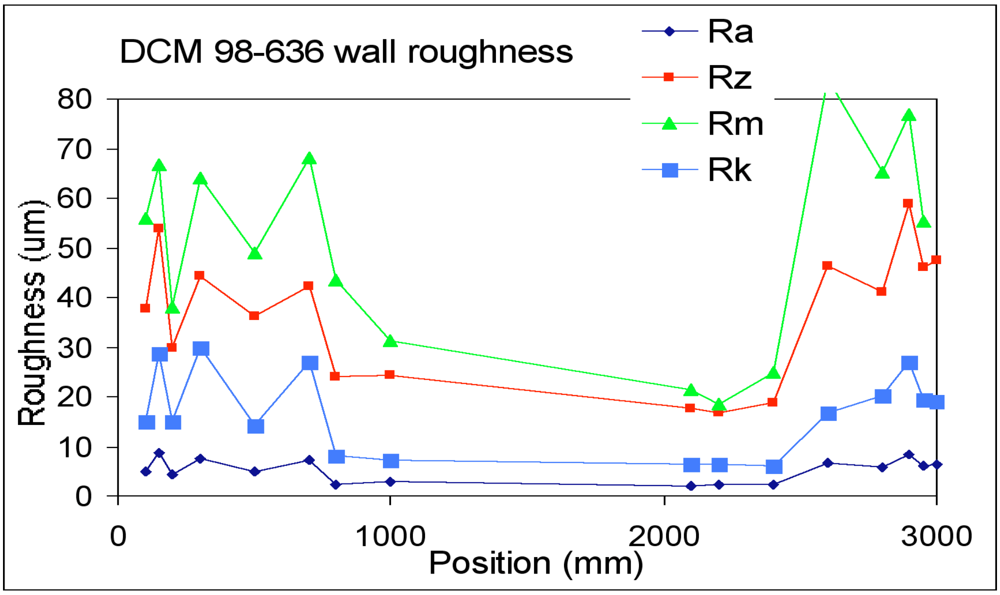

Figure 6, Wall roghness of pipe DCM 98-636

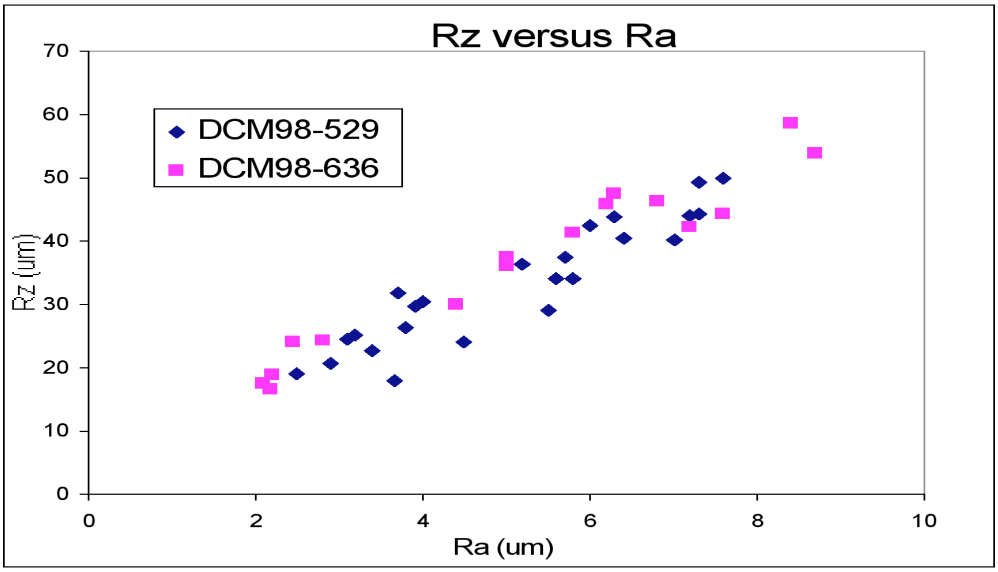

Figure 7, Correlation between R_z R_a

The pipe in test nr 1974.3 on August 28, 1998, belongs to the standard set of upstream pipes used during flow meter calibrations in the Pigsar facility. Its identification number is 218, and its date of manufacturing is unknown. It has a length of 5.10 m and its inner diameter is 310 mm. Like all the pipes in the Pigsar facility its inner surface has been sand blasted, in order to obtain a uniform wall roughness. Most of the surface is corroded, and therefore the wall roughness is considerably higher than that of the two Daniel tubes. At only one point, 50 cm from the flange, the roughness was within in the measuring range. R_a was found as 8.7 µm, R_z as 58.3 µm, R_m as 64.9 µm and Rk as 26 µm. At all the other locations the roughness was outside the measuring range of +60 to -100 µm. This means that R_a is definitely greater than 10 µm, probably 20 µm, according to Mr Laimmer.

Finally, test nr 1974.4 on August 28, 1998, concerned a very old pipe, manufactured in May 1978 by Barber Engineering, labeled 11.947, with a length of about 3.4 m and an inner diameter of 304 mm. Due to the heavy corrosion, the inner wall roughness exceeded the measuring range over the entire length of the pipe. No measured data could be obtained, so R_a far exceeds 10 µm, probably 20 µm, according to Mr Laimmer.

4 Flow Calibrations

All flow calibrations reported here were conducted at the Pigsar test facility in Dorsten, Germany, at an absolute gas pressure of about 45 bar. The first calibration took place on May 7, 1998. A 3-path Q.Sonic® ultrasonic flow meter (Instromet®), was mounted in line nr 2, directly downstream of pipe nr 218. The diameter of the flow meter is 0.3033 m, its serial number is 98Q06017, the spoolpiece was manufactured in the USA. The Final Factor of the meter was set exactly equal to one. The gas temperature was 16 C and the pressure was 45 bara. At each flowrate (given in actual m3/hr) three consecutive measurements were done of 100 seconds each, at the highest flowrate of 50 seconds each. The table lists the results.

Flow m^3/hr	Velocity m/s	1st point %	2nd point %	3rd point %
6100	23	0.160	0.110	0.172
5200	19.5	0.114	0.140	0.095
4000	15	0.048	0.121	0.057
2400	9	0.133	0.062	0.086
1600	6	0.078	0.027	0.042
800	3	0.174	0.183	0.121
400	1.5	0.577	0.538	0.523

The OIML weighted mean error equals 0.121 %.

Then the pipe nr 218 was removed and the DCM 98-529 pipe was mounted directly upstream of the ultrasonic flow meter. The calibration was repeated with this new upstream pipe, again at a pressure of 45 bara, but at a gas temperature of 14 C. This time the OIML error appeared to be -0.008 %. The next table presents the results.

Flow m^3/hr	Velocity m/s	1^{st} point %	2^{nd} point %	3^{rd} point %
6000	23	0.016	0.038	0.024
5100	19	-0.021	-0.112	-0.109
4000	15	0.028	0.044	-0.020
2400	9	-0.020	0.005	-0.047
1600	6	-0.055	-0.071	-0.046
800	3	0.048	0.036	0.065
400	1.5	0.516	0.376	0.392

Figure 8 shows the results, the graph is based on the Excel file from the Pigsar facility.

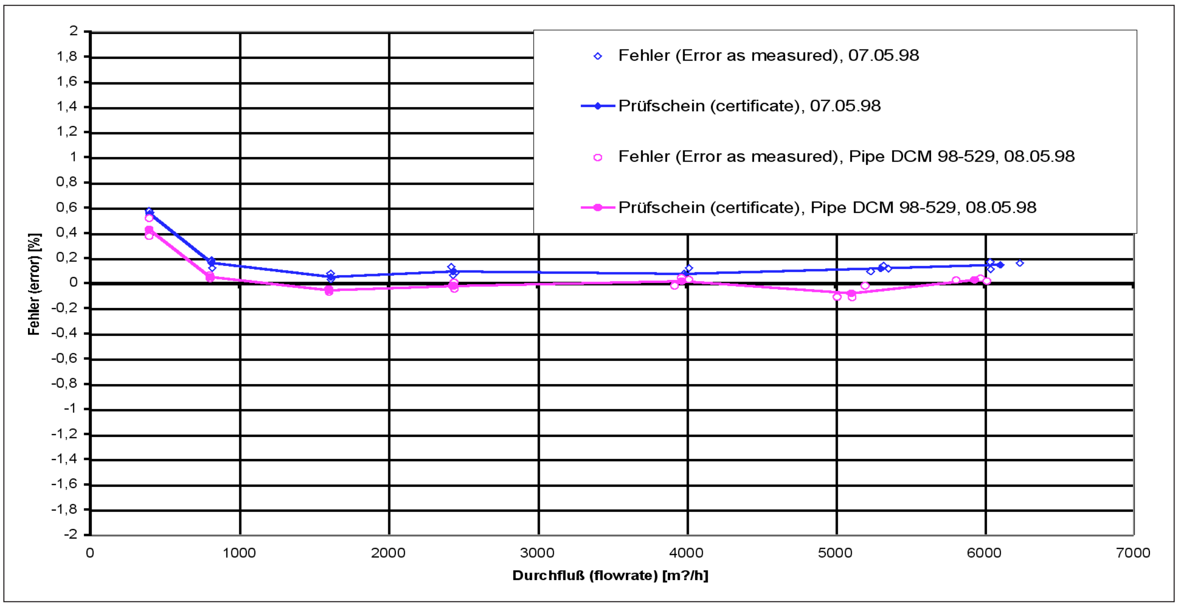

Figure 8, Calibration results of pipes 218 and DCM 98-529

The next series of tests started on August 25, 1998. A similar 3-path ultrasonic meter, serial number 98Q06104 was mounted on line nr 2, directly downstream of pipe DCM 98-636. The diameter of the flow meter is 0.3030 m, the spoolpiece was manufactured in the USA. The Final Factor of the meter was set exactly equal to one. The gas temperature was 11 C and the pressure was 45 bara, during the first calibration of the meter.

Based on the results shown in the table above, the Final Factor of the meter was adjusted by 0.2 % to 0.9980, after which the resulting OIML weighted error equals 0.0005 %. So the remaining errors can be found by subtracting 0.2 % from the entries in the above table. After this adjustment one more point at 400 m3/hr was measured as a verification that no errors had been made in the adjustment. The adjusted unweighted average over the flowrates of 5400, 2400 and 800 m3/hr equals -0.030 %. This value is important as a reference for the tests on September 1. First the base line of August 25 was checked with the DCM 98-636 pipe upstream of the meter. The gas temperature was 15 C and the pressure 45 bara. The next table lists the results.

Flow m^3/hr	Velocity m/s	1st point %	2nd point %	3rd point %
6100	23	0.245	0.175	0.220
5400	20	0.211	0.237	0.264
4000	15	0.223	0.146	0.262
2400	9	0.138	0.120	0.136
1600	6	0.064	0.081	0.092
800	3	0.149	0.160	0.119
400	1.5	0.131	0.057	0.007

The unweighted average is -0.086 %, which is an indication of the repeatability of both the meter and the facility. Then the old and dirty pipe, Barber Engineering labeled 11.947, was mounted directly upstream of the ultrasonic meter. The gas temperature was 14 C and the pressure was 43 bara, when the meter was calibrated at 5500, 2400 and 800 actual m3/hr. In this case the unweighted average is 0.041 %, which means an unweighted average shift of 0.127 %, the largest difference occurs at the highest flowrate.

Flow m^3/hr	Velocity m/s	1st point %	2nd point %	3rd point %	4th point %
5500	21	0.069	0.056	0.035	
2400	9	-0.100	-0.056	-0.096	
800	3	-0.230	-0.210	-0.148	-0.181

Then the DCM 98-636 was put back in place, to once more verify the stability of the meter reading, the results are shown below. Pressure was 46 bara, temperature 13 C. This time the unweighted average equals -0.096 %, which

Flow m^3/hr	Velocity m/s	1st point %	2nd point %	3rd point %	4th point %
5500	21	0.210	0.185	0.177	
2400	9	0.060	0.131	0.060	
800	3	-0.101	-0.091	-0.183	-0.030

again verifies that the meter and the facility are stable. The dirty Barber 11.947 pipe shifts the meter curve by about 0.1 to 0.2 % in upward direction. The graph below summarizes all results obtained on September 1, 1998.

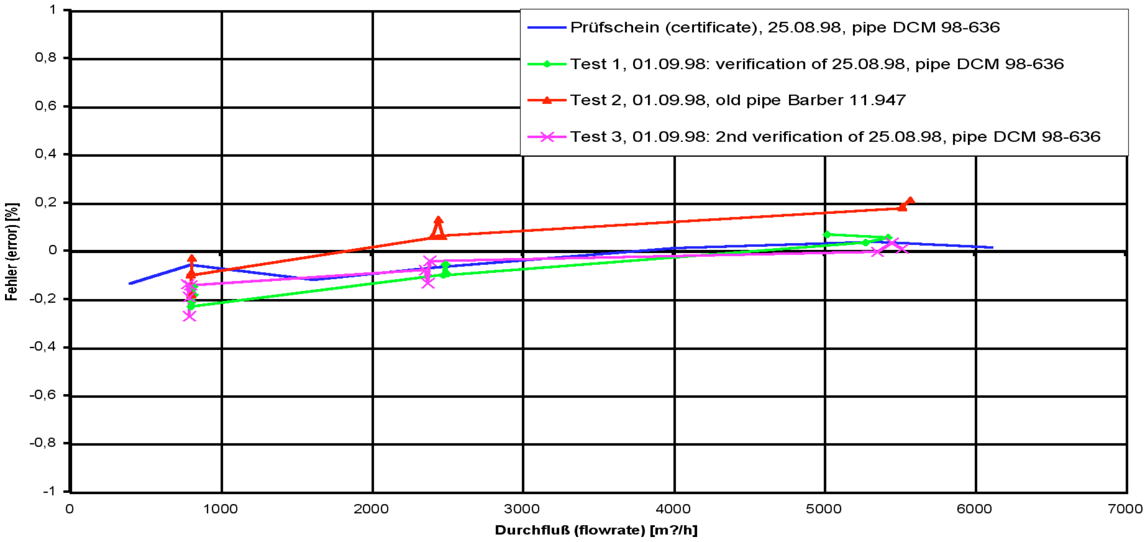

Figure 9, Test results of pipes DCM 98-636 and Barber 11.947

5 Conclusion

The results of the roughness measurements and the flow calibrations are summarized in the following table

Date	Pipe s/n	Pipe Ø (m)	Ra µm	Rz µm	Meter s/n	Error %	Mean
May 7	218	0.310	≥ 8.7	≥ 58.3	6017	0.121	OIML
May 7	529	0.303	5.1	33.3	6017	-0.008	OIML
Aug 25	636	0.303	5.2	36.6	6104	0.0005	OIML
Aug 25	636	0.303	5.2	36.6	6104	-0.030	3 pts
Sept 1	636	0.303	5.2	36.6	6104	-0.086	3 pts
Sept 1	947	0.304	20?	100?	6104	0.042	3 pts
Sept 1	636	0.303	5.2	36.6	6104	-0.096	3 pts

The date refers to the flow calibration, the roughness measurements were done on different dates. For August 25 the two rows differ in the way the error is calculated: in the first row it is the OIML weighted error based on all flow rates from 6100 to 400 m3/hr, in the second row it is an unweighted average over the three flowrates of 5400, 2400 and 800 m3/hr which are similar to those used on September 1.

The two pipes used on May 7 differ in two aspects: wall roughness and inner diameter. Recall that the diameter of the 98Q06017 flow meter itself equals 0.3033 m. It can not be excluded with complete certainty that the observed difference in meter reading of 0.129 % to some extent might be caused by the change of diameter rather than wall roughness. The effect of upstream pipe diameter is outside the scope of the present study, just like the possible interaction between upstream diameter and wall roughness.

In the second series of tests the two pipes have virtually equal diameter, so the observed difference of 0.128 % or 0.138 % quite likely is the result of wall roughness only. Now that we have reached this conclusion, we may take a second look at the May 7 data. Then it seems not unlikely that, whatever the interaction between diameter and roughness, the effect of a two percent change in upstream pipe diameter is of the same order of magnitude as the observed difference in meter reading, that is 0.1 to 0.2 %.

From the data obtained in the present investigation, the roughness of a 10 D pipe directly upstream of a 12» meter appears to have some influence on the reading of a 3-path ultrasonic meter. Over the range of conditions investigated, an increase of the roughness R_a from about 5 µm to probably 20 µm appears to increase the meter reading by about 0.1 - 0.2 %.

6 References

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