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VENTURI FOULING AND WHAT CAN CAUSE AN OVERESTIMATE OF THE FLOW RATE BY ONE PERCENT

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Abstract

In this study, we are looking for phenomena which can explain the effect that venturi fouling has on the measurement of feedwater flow rate in a PWR, Unit 3 of Ringhals Nuclear Power Plant, Sweden. When hydrazine is injected into the feedwater, it reduces the deposits of magnetite on the wetted surface of the venturi, and elsewhere at the given temperature ~200°C. This changes the reading from the flow measuring device and becomes closer to the originally calibrated data. Over time magnetite is rebuilt on the walls. We are searching for what can overestimate the mass flow rate in the order of 1%. Potential explanations are; changes in the venturi cross section area, change in properties of the fluid mixture, effects of suspended magnetite particles, changes in wall shear stress due to regular wall roughness, changes in the wall shear stress due to self-organized ripple wall roughness, changes in swirling flow due to wall roughness, separation in the diffuser part of venturi due to wall roughness, changes in the velocity profile (entering the venturi) due to wall roughness, and local buildup of deposits around the pressure taps.

Besides visual inspection of recently replaced venturi meters, numerical and theoretical estimates have been used to find the most likely explanation. We have derived a new wall function to introduce the self-organized ripple wall shear stress and used it in CFD (Computational Fluid Dynamics) simulations.

The first conclusion from the simulations is that the required regular wall roughness is not consistent with the observed thickness of the deposit on the wetted surfaces. Nor does the cross section area change sufficiently to make the flow rate deviate by 1%. The changes in fluid properties, due to the fluid mixing, are not significant. This is also true for a fluid with suspended magnetite particles. The only effect that is large enough to overestimate the flow by 1% is the self-organized wall ripple, for the observed deposit thickness. Also, we find that the deposit in the venturi has a larger effect on the mass flow rate reading, than the deposit in the pipe system upstream from the venturi. The wavelength of the self-organized ripple can be determined from the friction velocity, together with kinematic viscosity. That is, the wavelength is determined by fluid flow parameters.

Introduction

The flow rate measurement of feedwater using venturi meters can vary with the thickness of the deposit built up on the wetted surfaces, so called “fouling”. Exactly what this layer of deposit does is less well known to us. The layer is thin, but has yet a surprisingly large effect on the measured signal.

A number of factors have been listed as potential candidates to explain the reason why the venturi meter can drift from its calibrated curve. The objective of this study is to find which of the listed candidates can explain a deviation of the flow rate in the order of one percent.

The deposit consists of magnetite and is built up over time. This layer leads to erroneously high flow indications. The layer is also affected by hydrazine which is injected into the system, and dissolves magnetite partially. If the hydrazine concentration is increased, it can bring the reading closer to the original calibration curve. According to pH, ECP-measurements and thermodynamic data (pourbaix diagram) magnetite is the stable phase, but a further reduction can result in a dissolution of the magnetite (Fe^{2+}will be the stable phase). A high flow reading cause plant operators to reduce real flow in order to maintain the erroneous reading at a constant level, thus reducing plant power output, in order to stay within the limits the plant is licensed for.

1. Potential flow related reasons affecting the pressure difference reading in the venturi meter

An increased pressure difference indicates an increased flow rate. We are looking for an effect that can change the reading by 1% or more. Here we list some possibilities;

1. Contraction. How thick should the extra layer be to explain the increased pressure difference using the Bernoulli's equation?
2. Roughness. How rough must the walls be?
3. Self-organized wall ripple. Can it be a factor?
4. Do we have separation/reattachment in the diffuser due to extra wall friction?
5. Fluid properties. Density and viscosity change due to mixing with hydrazine?
6. Particles in boundary layer, extra friction?
7. Inlet rotation. How does the rotation of incoming flow change with roughness, and how much does it change the pressure difference reading?
8. Inlet velocity profile at inlet to the venturi meter?
9. Local deposition of magnetite around pressure-tap holes?

2. Investigation

2.1 Extra contraction due to fouling

The pipes leading to the venturi meter has an inner diameter 15.25 inches, i.e. 0.38735 m. The narrowest cross section of the venturi meter has a diameter of 8.1 inches i.e. 0.20574 m.

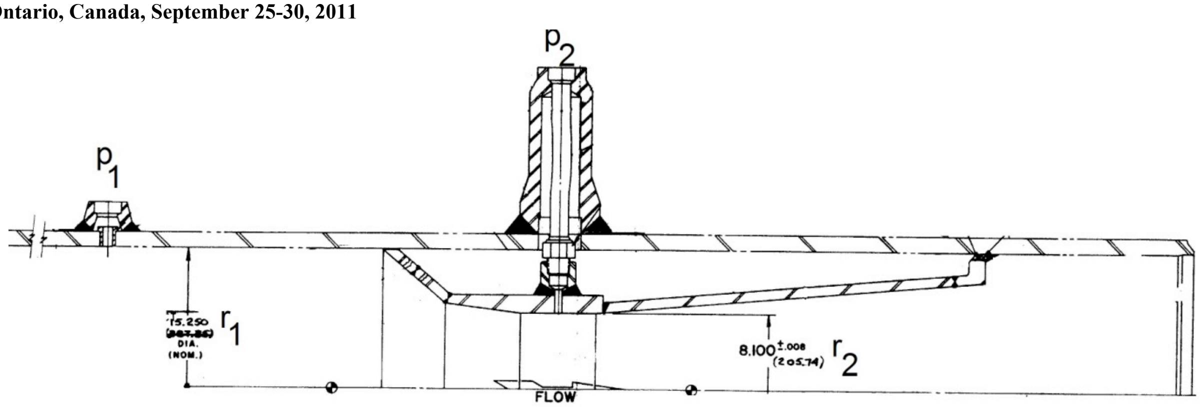

Figure 1 A drawing of the studied venturi meter.

The mass flow rate through a venturi meter can be approximated using the Bernoulli's equation. The mass flow rate can be written as a function of the pressure difference between the static pressure before the venturi meter, and the static pressure in the narrowest cross section of the venturi meter.

$$\dot{m} = \sqrt{\frac{2\rho(p_1 - p_2)}{\left(\left(\frac{1}{\pi\ r_2^2}\right)^2 - \left(\frac{1}{\pi\ r_1^2}\right)^2\right)}} \tag{1}$$

We are trying to find the extra thickness, δ, of an extra layer of oxide on the wetted surface, which would lead to a decrease in the mass flow rate to 99%, but where the pressure difference reading remains constant.

$$0.99\dot{m} = \sqrt{\frac{2\rho(p_1 - p_2)}{\left(\left(\frac{1}{\pi(r_2 - \delta)^2}\right)^2 - \left(\frac{1}{\pi(r_1 - \delta)^2}\right)^2\right)}} \tag{2}$$

The fraction of the two equations above can be written;

$$0.99 = \sqrt{\frac{\left(\frac{1}{r_2^2}\right)^2 - \left(\frac{1}{r_1^2}\right)^2}{\left(\frac{1}{(r_2 - \delta)^2}\right)^2 - \left(\frac{1}{(r_1 - \delta)^2}\right)^2}} \tag{3}$$

A good fit to this equation, in our case, seems to be, δ=0.5 mm. An observation; if the layer is assumed to be forming only in the narrowest cross section, δ would remain about the same. On the other hand, if the layer, δ=0.5 mm is put in the tube before the constriction, the mass flow rate would increase by a factor 1.00045, for a given pressure difference. A visual inspection in one of the venturi meters, shows that a thicker layer is built before, and after the narrowest cross section. The observed layer in the narrowest cross section does not appear to be 0.5 mm in thickness.

2.2 Wall roughness

Calculations have been made using CFD to study how rough the wall must be in order to explain a deviation of one percent in the flow rate. For this purpose the software ”Fluxion” [1] was used. The flow is fully developed through an inlet pipe with a length of one hundred diameters. Standard k-epsilon turbulence model is used.

Table 1 shows the apparent relative flow rate as a function of the equivalent sand roughness, k_s. For an increasingly rough surface, the pressure difference becomes greater, for the same mass flow rate. Interpreting the pressure difference through the Bernoulli's equation, it appears as if the mass flow rate has increased. The flow rate is however constant, in all cases, at a value of 550 kg/s. The Reynolds number is about $9 \cdot 10^7$.

Equivalent sand roughness, k_s, [mm]	Flow rate, relative to flow rate in a *smooth* pipe and venturi meter	Flow rate, relative to flow rate in *commercially rough* R/k_s = 1300 pipe and venturi meter
smooth	1	
0.1	1.0087	0.999
0.2	1.0115	1.0017
0.3	1.0140	1.0042
0.4	1.0159	1.0061
0.5	1.0177	1.0078
0.6	1.0189	1.0090
0.7	1.0204	1.0105
0.8	1.0216	1.0116
0.9	1.0227	1.0127
1.0	1.0237	1.0137
2.0	1.0317	1.0217
3.0	1.0376	1.0276
4.0	1.0425	1.0324
5.0	1.0468	1.0366

Table 1 Relative flow rate as a function of wall roughness

The surface of the venturi meter is not perfectly smooth. We don't have any information about the original wall roughness of the venturi meter was when it was calibrated. Therefore we assume the pipe and the venturi meter to be *commercially rough*. This is defined as R/k_s=1300, where R is the pipe radius. This corresponds to k_s=0.14 mm. If we are basing our relative flow rate on this roughness (column 3 in table 1), a one percent deviation in the reading of the mass flow rate, is obtained at an equivalent roughness of 0.7 mm. Again, this is not a thickness that has been observed in visual inspections.

2.3 Self-organized ripple

In cases where the flow is held at a constant rate, there is a possibility a self-organized ripple, with a dominating wavelength, to be formed on the wall. This is in the presence of an extra material which can be shaped by the flow. Examples of this can be found in [2], [3], [4] and [5]. In our case this material is magnetite. To be able to simulate this flow, it was necessary to derive a new wall-function to be used in the CFD calculations. Use has been made of the expression for the maximum friction coefficient as a function of the Reynolds number in pipe flow, presented in [2]. The details of this derivation will be put elsewhere. The CFD calculations have been performed in the same fashion as those performed for wall roughness.

Case	Flow rate, relative to flow rate over a *commercially rough* surface
Ripple in venturi meter and pipe	1.0083
Ripple in venturi meter, smooth pipe	1.0114
Smooth venturi meter, ripple in pipe	0.9876

Table 2 Relative flow rate dependence on self-organized ripple roughness

Table 2 shows the results for the relative flow rate interpreted from the pressure difference reading in the venturi meter, in the presence of wall ripple. The results indicate that the flow rate can be overestimated by nearly one percent if we have ripple in both the pipe and the venturi meter. The overestimate would be even greater if the pipe was smooth, but having ripple in the venturi meter. A surprising result is the fact that if the venturi meter is smooth, and the pipe has ripple, the flow rate is underestimated. This raises the question, is it wise to clean the venturi meter only?

The layer with ripple can be thin compared to the thickness of regular roughness, i.e. with no dominating wavelength, but still has the same effect on the wall friction and the pressure drop. An example of this can be found in [3], where ripples with an approximate height of 1 mm, had the same effect as 15 mm of regular roughness would have had on the pressure drop.

2.4 Separation

According to [6], in chapter XXIIa, a symmetric velocity profile is to be expected in a two-dimensional diffuser when the half opening angle is less than 4^{o}. An asymmetric velocity profile is achieved first when the half opening angle exceeds 4.8^{o}. Around 6^{o} separation occurs with reversed flow. Our geometry is axisymmetric and three-dimensional, with an estimated half opening angle of 5.2^{o}. No separation has been noted in the diffuser part of our venturi meter, in any of the numerical simulations.

2.5 Fluid properties

Hydrazine, N_2H_4, is mixed in the feedwater to reduce corrosion. The question is if the mix of hydrazine in water is large enough to affect the density and viscosity, and cause a change in the flow rate reading in the order of 1%.

The density and viscosity of hydrazine is close to that of water [7]. For example the density at 25 ^oC , 1 bar, is 1.0045 g/cm^3 (anhydrous) and 1.0322 g/cm^3 (hydrate). Water has the density, 0.997 g/cm^3, at 25 ^oC, 1 bar. The boiling point for hydrazine is 114 ^oC (anhydrous) , 119 ^oC (hydrate) at 1 bar, and for water the boiling point is 100 ^oC at 1 bar. The viscosity for hydrazine is 0.876 cP at 25 ^oC, and for water the viscosity is 0.92 cP at the same temperature. (10 P = 1 Pa*s.)

It is assumed that the two fluids have similar properties at other pressure levels and temperatures. To obtain a density difference large enough to affect the flow rate reading by 1%, the mix would have to consist almost entirely of hydrazine. Equation (1) shows the mass flow rates dependence of the density.

The difference in viscosity between the two fluids is small, and will not sufficiently change the Reynolds' number. We conclude that it is excluded that the injection of hydrazine could change the flow rate reading due to the change in mixed properties.

2.6 Particles

The particles in the streaming feed water is a mixture of magnetite~50%, hematite~40%, and β-/γ-FeOOH~10%. The oxide on the surface is a consolidatet magnetite. Could magnetite particles in the water affect the density and viscosity enough to change the flow rate reading in the order of 1%? Ishii and Zuber [8], have developed an expression for the viscosity, μ_m, for a mix of particles (or drops, or bubbles) in a fluid.

$$\mu_m = \mu_c \left(1 - \frac{\alpha_d}{\alpha_{dm}}\right)^{-2.5\alpha_{dm}(\mu_d + 0.4\mu_c)/(\mu_d + \mu_c)} \tag{4}$$

Index c stands for continues phase. Index d, is the dispersed phase. As a measure of the mix the volume fraction, α, is used. Maximal concentration of hard spherical particles is denoted, α_{dm}, and has been given the value 0.62. Viscosity, μ_d, for solid particles goes to infinity. For this case the value of the fraction, of the viscosities, in the exponent equals 1. Equation (4), can then be simplified to read;

$$\mu_m = \mu_c \left(1 - \frac{\alpha_d}{0.62}\right)^{-1.55} \tag{5}$$

We don't have the experience that the concentration of magnetite particles would be sufficiently high to make the value inside the parenthesis deviate much from unity. Thus the viscosity is not affected by the presence of magnetite particles. The magnetite particles, measured in less than 1 ppm, cannot change the mixing density to modify the mass flow rate reading by 1%.

2.7 Rotation

The venturi meters measuring the feed water in Ringhals power plant unit 3, are preceded by a number of pipe bends. They produce a secondary rotating flow. To see if this rotating flow has an influence on the flow measurements, a number of CFD calculations have been performed. The swirl, S, number has been chosen to quantify the strength of the rotating flow. The swirl number is defined as;

$$S = \frac{\int \rho U_x U_\theta r dA}{R \int \rho U_x^2 dA}. \tag{6}$$

To have a reference on the effect a rotating flow has on the measured flow rate, two simulations were performed on a straight pipe with a venturi meter. The simulations were done with and without a swirl. The swirl was generated by having an extra tangential inlet. The swirl number, S=0.05894, compared to swirl number, S=0.0, reduces the predicted flow rate from by 1.5 ‰, interpreted from the pressure difference between the two locations of the pressure taps.

Two CFD simulations have been performed in one of the loops, illustrated in figure 2, one simulation with smooth walls, the other with self-organized ripple on the walls.

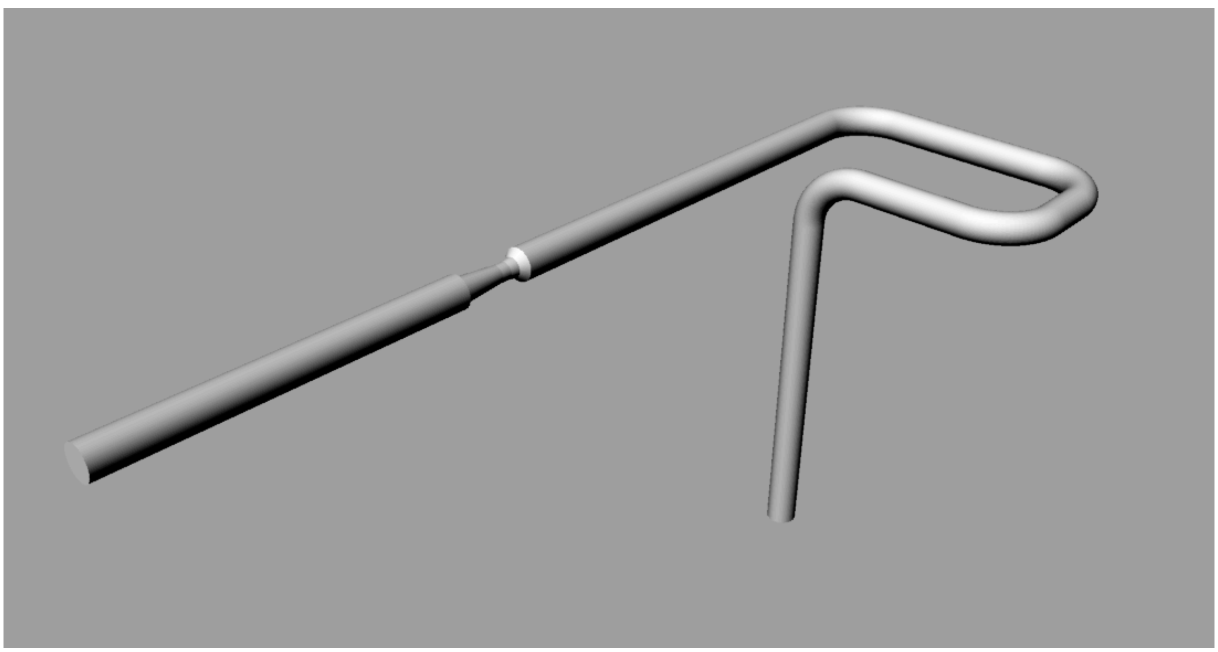

Figure 2 Venturi meter in one of three loops

The swirl number in both cases, see table 3, is lower than in the earlier runs, using a straight pipe. The effect of the rotation in the current geometry is therefore in the order, or less than, 1 ‰.

Loop in unit 3 Swirl number before the venturi meter
Smooth walls

S=0.0228
Walls with ripple S=0.0152

Table 3 Swirl number before venturi meter, with and without ripple

2.8 Velocity profile

How does the velocity profile at the inlet to the venturi meter affect the flow rate reading? We are going to revisit the results from section 2.2 and 2.3 in this paper, and study what the velocity profile was for some of those cases. Figure 3 shows the non-dimensional, fully developed, velocity distribution in the pipe upstream of the venturi, for different wall conditions. In this particular simulation the ratio of the pipe length to the diameter is 100, whereas at Ringhals NPP unit 3, the typical length to diameter ratio of the feedwater line is about 12. The fully developed flow profile depends on the pipe length to diameter ratio, and the Reynolds number, which here is about $9 \cdot 10^7$.

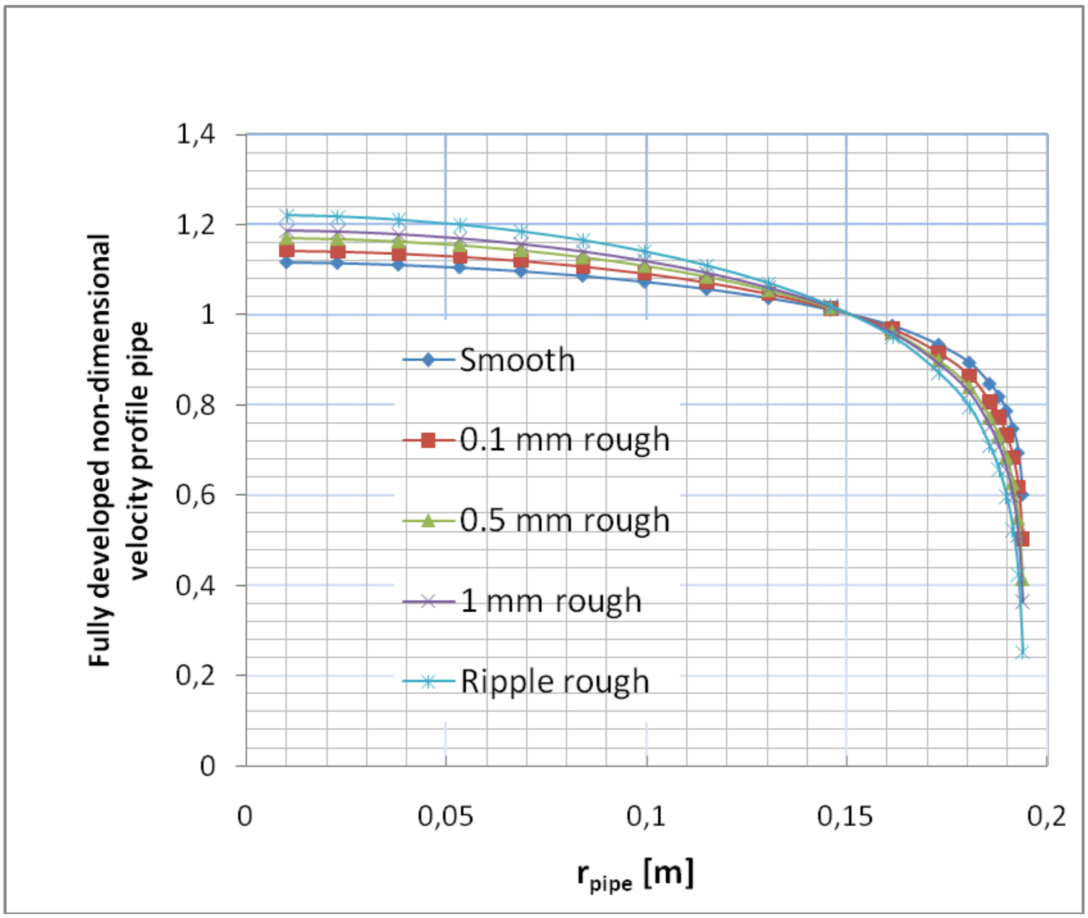

Figure 3 Velocity profile before venturi meter, for different surface structures

Figure 3 show that the velocity profile in the pipe with the ripple rough surface, has the highest centre velocity. It would be tempting to say that the higher the centre velocity is, the higher the flow rate reading is, even if the flow rate remains constant. In many cases this is true, but comparing the relative flow rate with 1 mm roughness in table 1, and the relative flow rate with walls having self-organized ripple in table 2, shows this is not true. Therefore currently we cannot make any general statement about the relation between the velocity profile and the deviation in the flow rate reading.

2.9 Accumulation in the vicinity of the pressure taps

Has so far, not been studied.

2.10 Visual inspection of the venturi meter

One replaced venturi meter from unit 3 was visually inspected. The inside was covered with black magnetite. There are some spots of red iron oxides as a consequence of outdoor storage, as figure 4 shows.

Figure 4 Photo of venturi meter viewed from diffuser end

It was observed that the surface is reminiscent of silicon carbide sandpaper due to coloring and touch. The structure of the surface has not been analyzed so far. We have compared the surface to different sand papers. At the outlet of the venturi the surface feels like the surface of sandpaper P320 or possibly sandpaper P400. The roughness at the narrowest cross section fells like sandpaper P1200. At the outlet the surface is black, but at the narrowest cross section, the surface has a lighter tone.

sandpaper	Average particle diameter ref.[7]
P320	46.2 µm
P400	35.0 µm
P1200	15.3 µm

Table 4 Sandpaper, grit size table

If ripple is present in the venturi, the expected dominant wavelength, λ, can be estimated from equation (7) taken from [5].

$$\lambda = 1000\nu / u_* \tag{7}$$

where ν is the kinematic viscosity, and u_* is the friction velocity. The friction velocity is defined by equation (8),

$$u_* = \sqrt{\tau_w / \rho} \tag{8}$$

where τ_w is the wall shear stress, and ρ is the density of the fluid. It is also possible to predict the wavelength based on the friction velocity on a smooth surface. The reason for this is that there appears to be an empirical relation, see equation (9), between the friction velocity on a smooth wall, and the friction velocity on a rippled surface, according to [5].

$$u_* = 2u_{*smooth} \tag{9}$$

For a given mass flow rate it appears the friction velocity is twice as high on self-organized ripple, as it would be on a smooth surface. From the current CFD simulations we can calculate the expected wavelength distribution in the venturi meter for a given Reynolds' number. See figure 5.

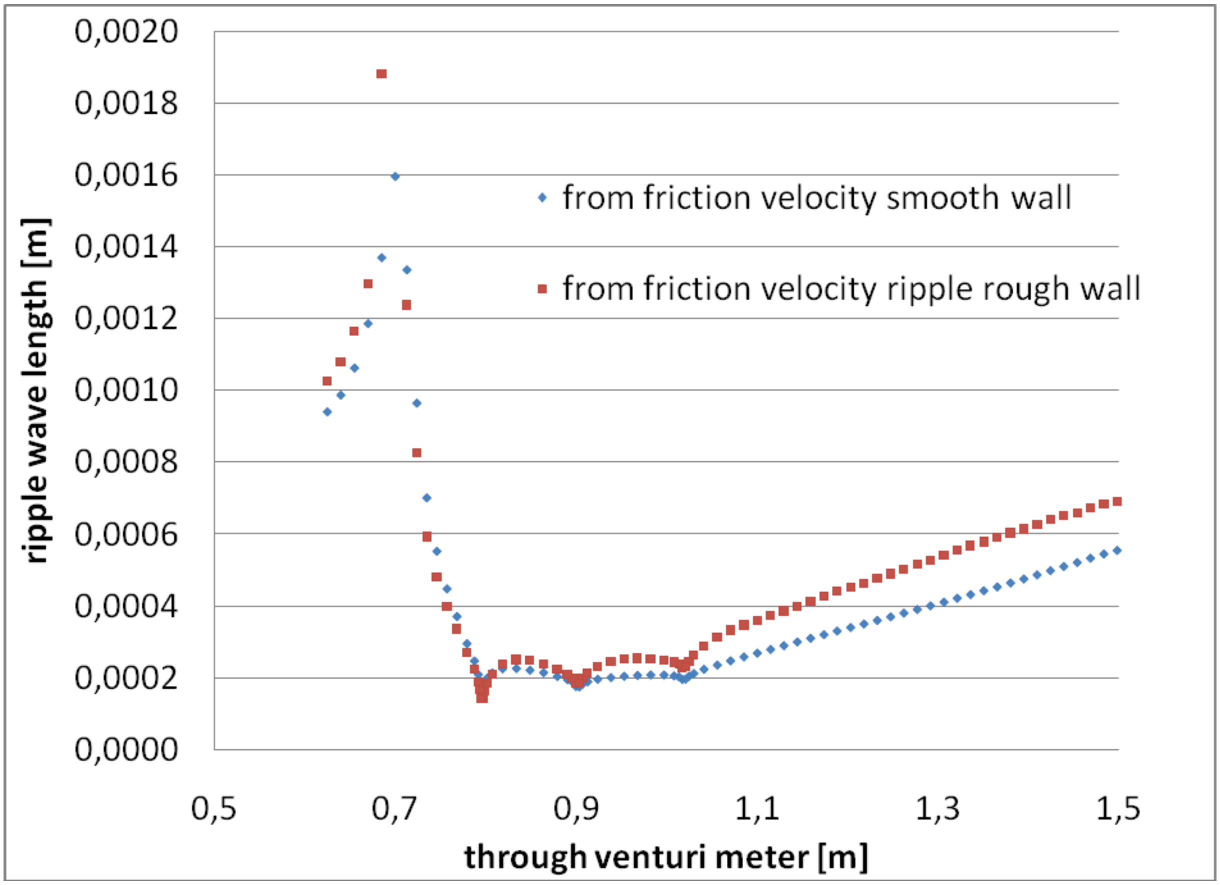

Figure 5 Predicted ripple wavelength distribution in venturi meter

In the narrowest cross section we predict a dominating wavelength of 200 to 250 µm. By comparing with roughness of sandpaper we estimate the ripple height to be about 15 µm. The ratio wavelength to wave height is then in the range 13 to 17. At the outlet we predict the wavelength to be 550 to 700 µm. Again using sandpaper as a reference, the wave height could be about 35-46 µm. The ratio wavelength to wave height would then be in the range 12 to 20.

Unfortunately we do not currently have any direct measurements, or images, of the surface structure in the venturi meter. Images of the type of ripple we are looking for can be found in reference [4]. The wavelength of the ripple in their experiment is consistent with the equation (7).

3. Conclusion

We conclude that, for the observed thickness of the accumulated magnetite layer, a self-organized rippled surface in the venturi meter is the only effect that can be strong enough to affect the flow rate reading in the order of 1%. We have identified a risk of underestimating the flow rate reading, if the venturi meter is cleaned, but the inlet pipe is not. We also found that the deposit in the venturi has a larger effect on the mass flow rate reading, than the deposit in the pipe system upstream from the venturi. The wavelength of the self-organized ripple can be determined from hydrodynamic quantities alone.

4. References

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