THE 12th INTERNATIONAL CONFERENCE ON FLOW MEASUREMENT

September 14~17, 2004,Guilin,China

IMEKO

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TC9

Chinese Society for Measurement Press

The 12th International Conference on Flow Measurement
Chinese Society for Measurement, September 2004

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FOREWORD

The world has now entered the information era, and information technology has become the key to promote the rapid development of science, technology and economy. Information is often obtained by measurement technology and measuring devices. If the information obtained has very large uncertainty, any subsequent transmission, storage and processing of it would be pointless. Measurement technology is therefore of crucial importance, and great attention should be paid to its development.

It is hardly necessary to express again the importance of fluid-flow-measurement technology. The amount of money involved worldwide is enormous. As more and more companies and people are entering the market for trade of liquids and gases, more and more custody-transfer operations occur. Environmental requirements also need more cost-effective flow-measurement devices. The desire to measure flow with decreased uncertainty and cost will continue to increase.

With this background FLOMEKO has grown to be the most successful series of conferences on flow measurement held in different venues around the world. FLOMEKO 2004, the 12th International Conference on Flow Measurement, is sponsored by IMEKO TC9 and organized by the Chinese Society for Measurement. It will be held in the Guilin Bravo Hotel, China, from September 14th to 17th 2004. During the conference 8 keynote lectures and more than 85 research papers from 17 countries will be presented to an audience of about 130 delegates from 20 countries.

The excellent scientific level of the papers at FLOMEKO 2004 will ensure that these proceedings will be a standard reference source for measurement engineers for many years to come.

We are sure that all of us that participate in FLOMEKO 2004 will long remember this FLOMEKO as a very interesting and enjoyable one.

We would like to thank all the contributors who participate in or support the activities of FLOMEKO 2004.

We would like also to thank Mrs Zhao Ruojiang, Prof. Sun Yanzuo, Mrs Wu Xiaomin, Mrs Zhao Xiaona, Mr Wang Dongwei, and others for their efforts to ensure the punctual publication of these proceedings for FLOMEKO 2004.

You are warmly welcome to Guilin and we hope you enjoy FLOMEKO 2004.

Dr. Wang Qinping

王秦平

Chairman of Organizing Committee, FLOMEKO 2004

Dr Michael Reader-Harris

Michael Reader-Harris

Chairman of IMEKO TC9;

Chairman of International Programme Committee, FLOMEKO 2004

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Velocity Profile Effect on Woltman Water Meters Performance

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Abstract: This paper describes a detailed study, covering analytic as experimental aspects, about the effect on a commercial Woltman meter of different hydraulic fittings and configurations such as butterfly and gate valves. Firstly, a three-dimensional numerical simulation using computational fluid dynamics techniques (CFD) is used to calculate the alteration of the velocity profile by upstream fittings. Afterwards, the theoretical analysis undertakes the study of blade forces and torques generated by the fluid flow (Baker, 2000). Finally, laboratory test validate the analytical procedure proposed.

Keywords: Woltman water meter; flow distortion; accuracy meter; Computational Fluid Dynamics

1. Introduction

Woltman water meters are frequently installed in water distribution networks. These instruments are used as flowmeters for measuring the injected water to district metering areas and as water meters for industrial and commercial users. Its operating principle is, basically, the same as the turbine flowmeters which have been widely studied in the technical literature. However, these instruments are specially designed to work with water and to integrate the flow rate and provide the total water consumed over a period of time.

Often, the straight length of the pipe situated upstream the water meter is not sufficient to guarantee a fully developed velocity profile. Even though, an improper installation of the Woltman water meter can lead to significant measurement errors. Technical literature about the magnitude of these error is difficult to find. Maybe one reason is because it is not easy to extrapolate conclusions obtained from one meter to other designs. The internal geometry of the meter vary the influence that a distorted velocity profile causes on its performance. The angular velocity of the turbine is a function of the driving torque generated by the fluid. This driving torque depends on the velocity distribution along the section and, also, on the blades and turbine geometries. A distorted flow will modify the driving torque at a given flow rate, changing the original relationship between the actual flow rate and the angular velocity of the propeller. The influence on the accuracy curve of the meter will be different for each model and flow distortion.

This paper describes a theoretical methodology that estimates qualitatively the effect of flow distortions on the accuracy curve of the instrument. The analytical results have been validated by experimental testing of the water meter.

2. Theoretical approach

The primary element of a Woltman water meter is a turbine whose rotational speed is directly proportional to the volumetric flow rate [1]. The angular velocity of the turbine, which is connected directly to the register gears, depends on the incidence angle and the impact velocity of the water passing through the meter. A fully developed velocity profile will result in a distribution of driving forces with axial symmetry around the turbine. This way the resulting force in a portion of the turbine is independent of the circular sector considered.

In a steady state, this driving torque is in equilibrium with the drag torque caused by the bearing, the hub disk friction, the tip clearance and the hub fluid drag[7]. This drag torque may be estimated for a constant rotational speed of the turbine from the driving torque calculated for a fully developed flow profile.

It is clear that this approximation is only completely valid when the flow distortions are not severe but it may be also qualitative good estimated when the flow profile is disturbed. In this case, the larger the disturbance the more incorrect is the proposed approximation for the drag torque.

Therefore, the first step in the methodology is to perform a three-dimensional numerical simulation using computational fluid dynamics techniques (CFD), to calculate the velocity profile resulting from the installation of upstream fittings. Afterwards, through airfoil theory, it is possible to calculate theoretically the forces and torques in the turbine produced by diverse flow conditions [2].

2.1. Flow simulation

The method uses Computational Fluid Dynamics (CFD) as a tool to calculate water velocity profiles at different sections of the pipe. In particular, the principal purpose of modelling the flow through CFD software is to determine water velocity profiles after a gate or a butterfly valve with several closures and two different lengths of straight pipe between the valve and the meter. The CFD software used for modelling the flow was FLUENT[3].

Recently, the use of CFD as a tool for hydraulic analysis to predict the flow behaviour inside a pipe is becoming more frequent. Combining the modelled flow in different pipe configurations with the instrument operating principle, it is possible to evaluate the influence of flow distortions on the accuracy curve. Up to day, several studies have been published in which the performance of several flowmeters is estimated from velocity profiles calculated with CFD software. Examples are the reports published by the National Engineering Laboratory [5] for insertion probes and clamp-on ultrasonic meters.

During the study, a classic model, RANS (Reynolds Average Navier-Stokes), was used to simulate the turbulent flow. The turbulence model chosen (governed by Navier-Stokes equations) was the two equations k -ε model with the standard parameters [8]. This approach[4] defines the turbulent viscosity (μt) with only two equations. Table 1 shows the configurations that were simulated and the parameters used during the numerical analysis. Basically, the influence of two types of valves with different closures was tested.

Table 1. Flow simulation test and boundary conditions established.

	Reference test	Gate valve			Butterfly valve	
Opening	-	75% closed	50%	25% closed	Open	30º closed
Distance between elements	-	0D	0D	0D	-	-
		3D	3D	3D	3D	3D
Boundary conditions						
Inlet velocity (m/s)	1,2,3,4,6	1,2,3,4,6	1,2,3,4,6	1,2,3,4,6	1,2,3,4,6	1,2,3,4,6
Outlet pressure (bar)	3	3	3	3	3	3
Wall roughness k (mm)	0,1	0,1	0,1	0,1	0,1	0,1

Some of the results of the numerical analysis, which facilitate the understanding of the flow behaviour and the influence of the fittings on the velocity profiles that reach the meter, are depictured in figures 1 to 4. The CFD simulations do no include the moving internal parts of the meter and only consider the water meter hub and straighteners. This simplification reduces enormously the computational time required to solve the problem and should not significantly affect the results as long as the incidence angle of the water jets and the blades are small.

For the Woltman meter studied, when the flow profile is not distorted, the incidence angle is lower than 7° (Figure 9). Therefore, in this case, the turbine influence on the upstream flow profile should be also small and the assumption may be considered correct. However, if the flow profile is highly distorted, the incidence angle may change considerably and the effect of the turbine on the upstream velocity distribution may not be negligible.

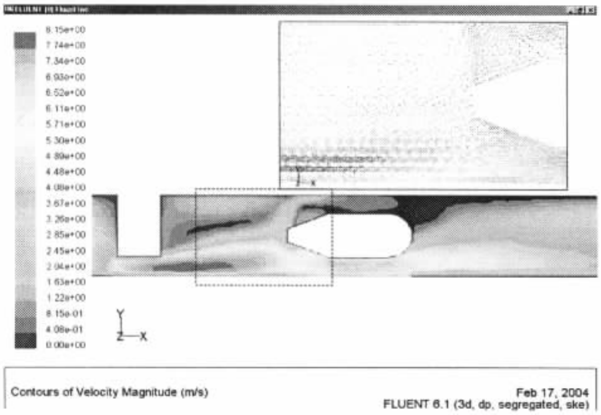

Figure 1. Longitudinal section of the pipe and meter. Velocity vectors across a partially opened gate valve upstream a Woltman meter (0D).

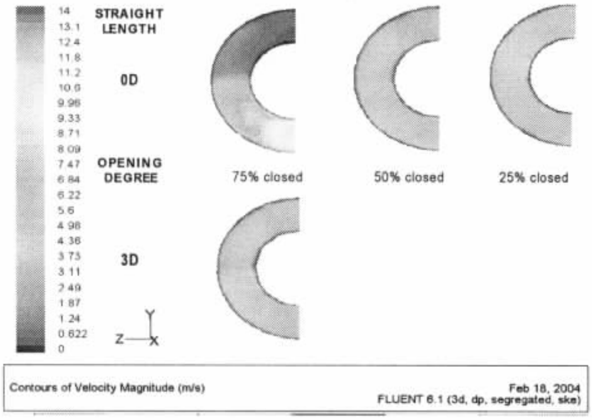

Figure 2. Water flow distortion in the meter, upstream the turbine, caused by a gate valve with different openings.

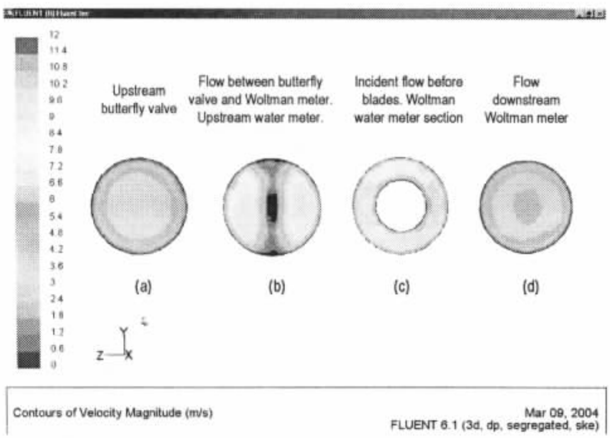

Figure 3. Water flow distortion caused by a fully opened butterfly valve installed 3D upstream the meter.

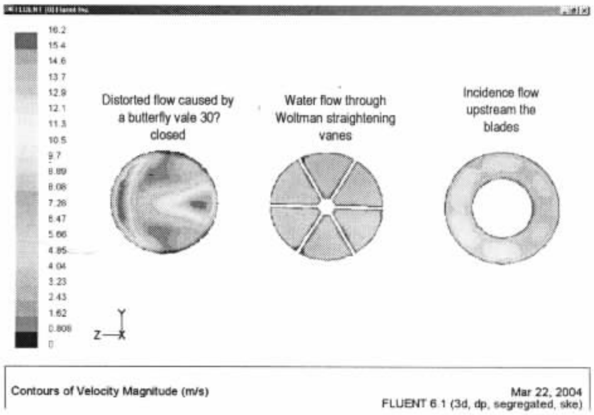

Figure 4. Velocity contours through a partially opened butterfly valve installed 3D upstream the meter.

The previous figures show the velocity profiles upstream the turbine of the Woltman after passing through a gate valve (Figures 1 and 2) and a butterfly valve (Figures 3 and 4). As it is seen, for a gate valve installed upstream the meter only when it is 75% closed the flow distortion is significant. When the butterfly valve is fully opened and it is installed at a distance of three diameters from the meter, the velocity distribution it is not considerably affected. A similar result is obtained when the butterfly valve is 30° closed.

2.2. Theoretical force analysis

By means of airfoil theory [2] it is possible to calculate the forces that water exerts on differential areas of the turbine blades. Integrating these forces through the blade surface and extending the integration to the whole turbine area (equation 1) the total driving torque can be predicted.

$$T_{axis} = \frac{1}{2} \iint \rho \cdot L_c \cdot W^2 \cdot (C_z \mathrm{sen}(I) - C_x \cos(I)) \cdot r \cdot dr \qquad (1)$$

Where Lc is the length of the blade that, for the Woltman meter studied, is a function of the distance to the axis, ρ the fluid density (Kg/m^3), W the incidence velocity of water on the blade (Figure 6), U the tangential blade velocity, V the axial water velocity, Cx and Cz are, respectively, the drag and lift coefficients and I the angle that forms the incidence velocity with the vertical (Figure 6). The theoretical formula given for the lift and drag coefficient by several authors for a cascade of flat blades is

$C_z = 2\pi \sin(i/2)$ and Cd=0 [6]. Being i the incidence angle between water and the blade.

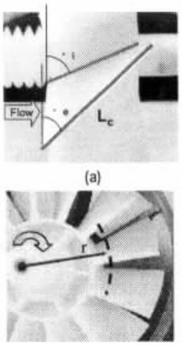

Figure 5. Horizontal Woltman turbine meter. Lateral view (b) Frontal view

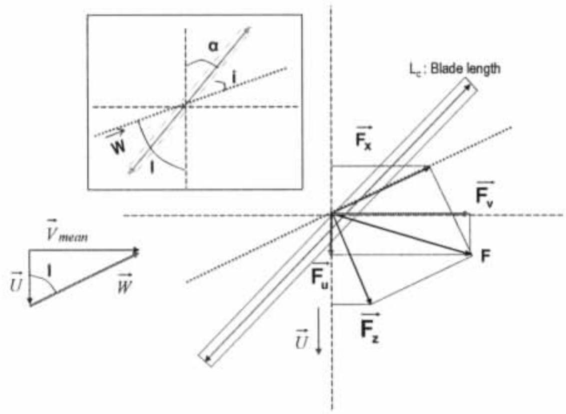

Figure 6. Forces arriving to Woltman meter blades

As previously said the numerical procedure estimates a theoretical driving torque (equation 1), for a given flow rate, with a stationary and fully developed velocity profile. In a steady state, this torque is equal to the drag torque associated to the corresponding angular velocity of the turbine. Then, it is possible to build a drag characteristic curve of the meter as a function of the rotational speed of the turbine (Figure 7). The drag forces are intrinsic to each instrument and depend on the geometry and design of the turbine (Figure 5).

Once the drag torque is known, the next step consists of estimating the effect of a distorted flow on the accuracy of the meter. The procedure only needs to compare the driving torque generated by a distorted flow with the drag torque associated to the nominal angular speed corresponding to that flow rate. If these parameters are not equal, the driving torque is recalculated with a different angular velocity of the turbine and then compared again with the drag torque associated to the new rotational speed. This procedure is repeated until it is found an angular velocity such that both torques are equal (Figure 8).

Then the error change at that flow rate for the distorted flow is easily calculated (equation 2). At this point, it is convenient to remark that the proposed method supposes that a fully developed flow profile will be measured by the meter with no error, independently of the flow rate as long as it is turbulent. If the rotational velocity at which the equilibrium is reached is larger than the nominal one the error will be positive, otherwise the error will be negative.

$$\varepsilon_Q = \frac{\omega_{\text{distorted flow}} - \omega_{\text{fully developed flow}}}{\omega_{\text{fully developed flow}}} \quad (2)$$

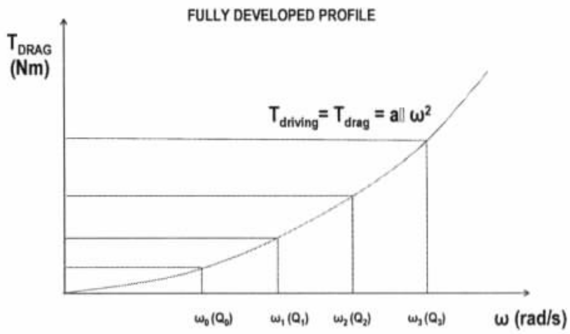

Figure 7. Woltman meter drag torque in a fully developed flow.

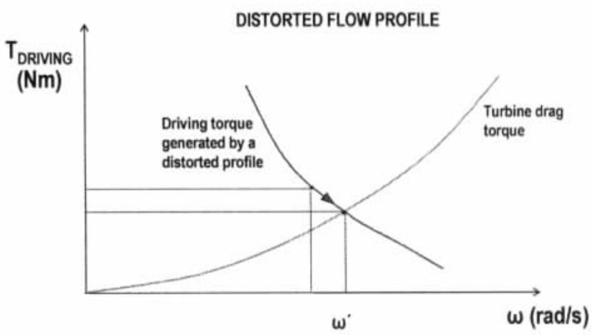

Figure 8. Iterative procedure to estimate ω for a distorted flow.

About the limitations of the proposed methodology, it is important to mention that the driving torque depends on the velocity profile upstream the turbine and the incidence angle. If the flow is highly distorted the incidence angle may vary from the design one (Figure 9). Since the rotating turbine is not included in the model, for these cases, the incidence angle may not be negligible and the blade may have a considerable influence on the upstream flow. Therefore, for greatly distorted flows, the actual driving torque may differ considerable from the calculated one. Finally, the estimated drag torque (Figure 7) in highly distorted flows is probably significantly different than actual one.

2.3. Results

As seen, from the numerical simulations of the flow and the theoretical analysis presented it is possible to estimate the influence of different flow distortions in the accuracy of a Woltman meter. Following, the results obtained for a real Woltman meter are described.

The incidence angle of water at different sections was calculated using these velocity profiles, obtained from the numerical simulations, the blade geometry and the theoretical rotational speed of the turbine. Under a fully developed flow the approaching velocities and incidence angles have an axial symmetry and basically depend on the distance to the pipe axis. Consequently the driving forces are equilibrated and its contribution to the total driving torque is similar in every slice of the turbine. As depictured in Figure 9 the incidence angles are relatively low, smaller than 7 or 8°, and almost independent of the radius.

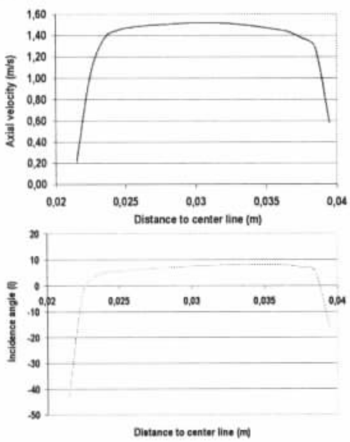

Figure 9. Axial velocity and incidence angle for a fully developed flow profile.

However at the inner and outer side of the blades, at the hub and the tip, the incidence angle becomes negative which means that at these zones the local force opposes the turbine rotation (Figure 10).

The explanation for this effect is simple. The direction of the velocity at which the water impacts the blade (W) is the result of the composition of the approaching water velocity (V) and the tangential velocity of the blade (U). The incidence angle (i) is the angle that forms the relative velocity of the water upstream the turbine and the blade (W) (Figure 6). Since the axial velocity at the hub and the tip is small and decreases when the water comes closer to the wall, the angle I also decreases becoming at some points smaller than α. As a result, the incidence angle is negative especially at the hub. The tip clearance between the blade and the meter wall mitigates or eliminates this effect at the end of the blade.

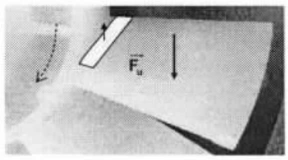

Figure 10. Driving forces at the blade.

Table 2. Meters predicted accuracy for different configurations

WOLTMAN WATER METER			
Gate valve		**0D**	**3D**
	75% closed	44,4%	2,0%
	50% closed	1,9%	
	25% closed	-0,8%	
Butterfly valve			**3D**
	Open		-0,5%
	30?closed		-0,5%

For calculating the error of the Woltman meter when the velocity profile is distorted it is supposed that under ideal flow conditions the meter has a linear response and the error at any flow rate in a turbulent regimen is zero. Table 2 shows the results of the estimated error of this Woltman meter for several configurations.

It was concluded that for a gate valve installed just upstream the meter, the average metering error increased with the closing of the valve.

When the gate valve was closed approximately 25%, the performance of the meter was not affected. When the closing of the valve reached the 75% the metering error increased to 44.35%. However, it is significant that the theoretical analysis concluded that when the valve was half closed the error was only of 1.85%. That would mean that this type of meter was not significantly affected by the flow distortions caused by a gate valve as long as it is not closed more than 50%. With the same procedure, it was also concluded that when the gate valve was installed three diameters upstream the water meter, the discrepancies only increased by 2%.

After obtaining these results further investigation was carried out for the configuration in which the gate valve is installed right upstream the meter and is 75% closed. In first place, an important distortion in the flow profile was detected. Figure 11a and Figure 11b show the velocity profiles in two rakes, one in the upper part of the pipe and the other in the lower part. For an average velocity of 8 m/s, which corresponds approximately to a flow rate of 100 m3/h, the flow velocity in the upper section is less than 1 m/s while in the lower it is greater than 14 m/s, with an incidence angle, i, close to 16°. Due to the low velocity, the incidence angle in the upper part of the pipe is negative, which means that the driving forces are opposed to the rotation of the turbine, while in the lower part the driving forces greatly increase with respect a fully developed flow profile.

As an example Figure 11b and 11d, represent the increment in momentum produced by the flow distortion in two rakes. It is clear that in this case the total torque rise in the lower part is greater than the momentum lost in the upper section. For that reason the metering errors become positive.

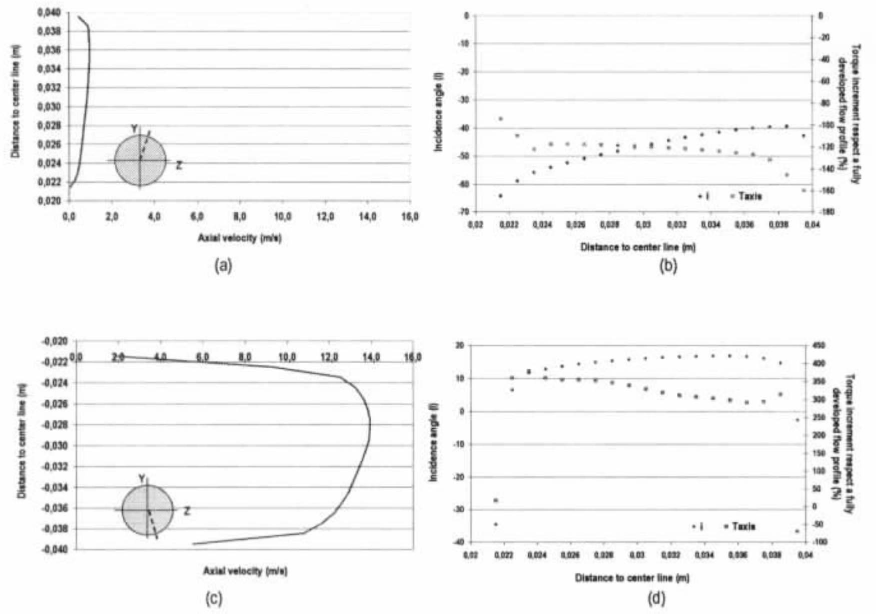

Figure 11. Two side velocity profiles and torque variation compared to a fully developed flow.

Finally, the theoretical errors obtained when the flow distortion is caused by a butterfly valve fully open and partially closed (30°) at a distance of three diameters are approximately of -0.5%.

3. Laboratory tests

The theoretical results were validated against a set of laboratory tests. In general, the laboratory results show a consistent performance of the instrument.

Only when the velocity profile is greatly distorted by a gate valve 75% closed, installed just upstream the meter, some positive errors are observed. However the magnitude of this error, approximately of +4%, is much less than the predicted one of +45% (Figure 12). It was also checked in the laboratory that when the closure of the gate valve was greater than 92% the error was approximately +40% (Figure 15).

The accuracy curves of the meter show that as the distortion of the velocity profile decreases, because the perturbing element is further away from the meter or the closure of the valve is smaller, the measuring error is more similar to the one obtained under a fully developed flow (Figure 12). The flow distortion originated by a butterfly valve installed three diameters upstream the meter does not cause significant measuring errors (Figure 14).

The experimental results prove that a distance of three diameters of straight pipe upstream this Woltman meter is enough to assure a good measurement, accurate in ±2%, when the flow distortion is caused by a butterfly or a gate valve. These results are similar to those obtained by the theoretical calculations following the method explained in section 2.

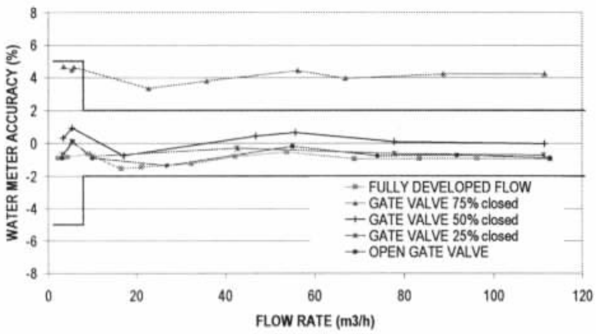

Figure 12. Laboratory tests. Woltman 80 mm. Gate valve installed 0D upstream the meter.

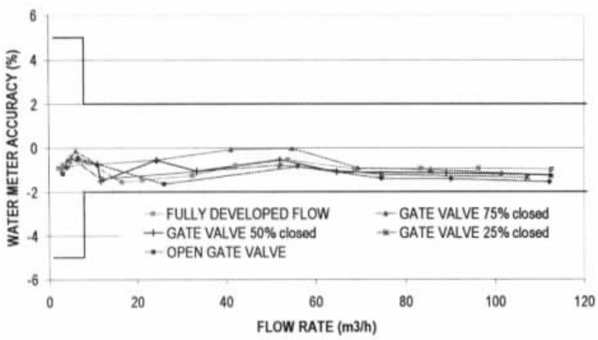

Figure 13. Laboratory tests. Woltman 80 mm. Gate valve installed 3D upstream the meter.

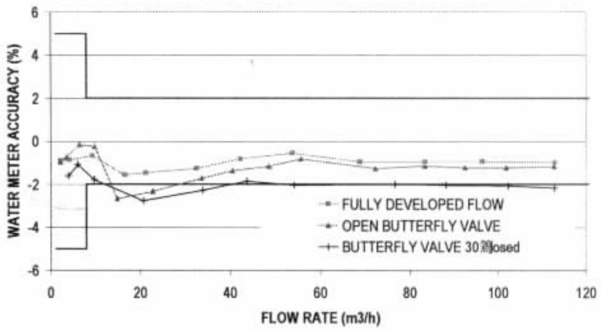

Figure 14. Laboratory tests. Woltman 80 mm. Butterfly valve installed 3D upstream the meter.

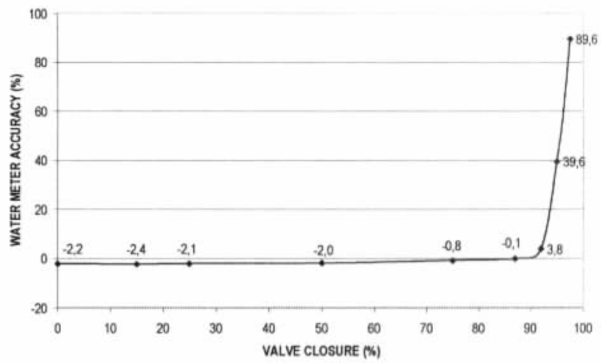

Figure 15. Laboratory tests. Woltman 80 mm. Gate valve installed 3D upstream the meter.

4. Conclusions

Even these days many flow measuring devices commonly used in water supply systems are inappropriately installed. Most of the times due to the lack of knowledge of the technical staff that are not familiar or do not follow the manufacturer recommendations about the installation and maintenance of the instruments.

Woltman meters, which can be considered as a type of turbine flowmeters are sensitive to the approaching flow profile quality. However, there is not much knowledge of the effect of flow profile distortions on the accuracy curve of these meters. This paper presents a theoretical methodology for estimating the measuring errors of a Woltman meter in different configurations.

The methodology applied in this case to a gate and a butterfly valve can be extended to estimate the performance of Woltman meters under the effect of other flow disturbances.

The method uses CFD techniques for calculating the velocity profile upstream the turbine of a Woltman meter and after the flow distortion. A theoretical drag torque for different rotational speeds of the turbine is estimated from the driving torque generated by a fully developed flow. The driving torque is calculated using airfoil theory (equation 1). This estimated drag torque, associated to a specific angular velocity of the turbine, is then compared with the driving torque generated by the distorted flow profile to calculate approximately the over or sub registration of the meter.

The theoretical conclusions have been contrasted with several laboratory tests of the meter. In all configurations the results obtained by both procedures, theoretical and experimental, are quite similar except for that in which the flow distortion upstream the turbine section is significant, when the gate valve is 75% closed and it is installed just upstream the water meter. In this case the predicted error at several flow rates was of +45%. However the actual error of the meter proved to be much lower, of only +4%. The assumptions adopted during the procedure explain this discrepancy. In this sense it is important to highlight that the theoretical analysis performed in this paper is only a qualitative analysis and does not intend to predict exactly the real accuracy of the meter.

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