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ТЕОРЕТИЧНО И ЕКСПЕРИМЕНТАЛНО ИЗСЛЕДВАНЕ НА СКОРОСТТА НА ПОТОКА ЧРЕЗ УЛТРАЗВУКОВ И ВИХРОВ ДЕБИТОМЕР

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Резюме: *Настоящото изследване сравнява измерванията на скоростта на потока от ултразвуков дебитомер тип clamp-on, работещ по метода на преходното време и вихров дебитомер. За референтно устройство е използван магнитно-индуктивен дебитомер. Скоростта на потока се изчислява посредством регулирания обемен дебит и сечението на измервателната тръба на всеки дебитомер. Анализът разглежда отклонението между изчислената и измерената скорост, както и зависимостта между честотата на вихрообразуване и скоростта на потока. Неопределеността при измерванията се дефинира в съответствие с ISO/IEC Guide 98-3 (ISO-GUM). Експерименталните резултатите представят добро съгласуване с теоретично получените стойности в границите на разширената неопределеност. При ултразвуковия дебитомер най-голямо отклонение се наблюдава при ниски скорости на потока, достигащо приблизително −7%, в следствие на малката разлика в преходните времена и разделителната способност на устройството. При скорости над 0.4 m/s, потокът е напълно турбулентен и измерванията са по-надеждни. Вихровият дебитомер следва друга зависимост, след установяване на устойчиво вихрообразуване, при скорости над 1.4 m/s, отклоненията се минимизират. Отчетените разлики между изследваните дебитомери са свързани основно с принципите на измерване, а не със систематични грешки.*

Ключови думи: *измерване на скоростта на потока; ултразвуков дебитомер с измерване на преходно време; вихров дебитомер; неопределеност при измерване.*

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THEORETICAL AND EXPERIMENTAL STUDY OF FLOW VELOCITY MEASUREMENT USING ULTRASONIC AND VORTEX FLOWMETER

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Abstract: *This study compares velocity measurements obtained from a clamp-on ultrasonic transit-time flowmeter and a vortex flowmeter. An electromagnetic flowmeter is used as the reference device. The theoretical flow velocity is determined from the regulated volumetric flow rate and the measuring tube diameter of each flowmeter. The analysis examines the deviation between calculated and measured velocities and the relationship between vortex-shedding frequency and flow velocity. Measurement uncertainty is defined in accordance with ISO/IEC Guide 98-3 (ISO-GUM). The experimental results demonstrate good agreement with the theoretical values within the range of expanded uncertainty. For the ultrasonic flowmeter, a largest deviation is observed at low velocities, reaching approximately −7%, where the small transit-time difference limits measurement resolution. At velocities above 0.4 m/s, corresponding to fully turbulent flow conditions, the measurements become more reliable. In contrast, the vortex flowmeter exhibits a different behavior. Once stable vortex shedding is established, at velocities above 1.4 m/s, the deviations are minimized with increasing velocity. The main differences between the flowmeters are primarily attributed to their underlying measurement principles rather than to systematic bias.*

Keywords: *flow velocity measurement; ultrasonic transit-time flowmeter; vortex flowmeter; measurement uncertainty.*

1. Introduction

Flow velocity measurement is essential for water distribution, industrial process control, and thermal energy systems. Among the available methods, ultrasonic transit-time and vortex flowmeters are widely adopted because they are robust, require relatively little to no maintenance, and can operate under demanding industrial conditions [1,10].

Ultrasonic transit-time flowmeters determine velocity from the difference between upstream and downstream acoustic travel times (Δt). Their clamp-on design is useful when non-intrusive installation is required. However, the accuracy depends on factors such as acoustic path geometry, flow profile, and transit-time resolution. These effects become more significant at low flow velocities [1,2,6,11,12].

Vortex flowmeters determine velocity from the shedding frequency of vortices generated behind a bluff body placed in the flow path. This principle follows the Strouhal relation, which describes the relationship between vortex shedding frequency and flow velocity over a wide range of Reynolds numbers [3,4]. For this reason, these devices are well suited to fully developed turbulent flow in closed pipeline systems. Although both technologies have been studied extensively, fewer research directly compares theoretical velocity, ultrasonic

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measurements, and vortex measurements under the same hydraulic conditions, especially when uncertainty propagation is included.

This study presents an experimental comparison of theoretical, ultrasonic, and vortex-based velocity measurements under the same conditions, with an explicit uncertainty analysis.

2. Theoretical Background

This section summarizes the theoretical relations used to interpret the measured velocity data and to compare the operating principles of the reference electromagnetic, ultrasonic transit-time, and vortex flowmeter.

2.1 Flow Velocity

For incompressible flow in a circular pipe, the average velocity v_{th} is obtained from the fluid velocity equation:

$$v_{th} = \frac{Q}{A} \tag{1}$$

where Q is the volumetric flow rate and A is the internal cross-sectional area of the pipe:

$$A = \frac{\pi D_i^2}{4} \tag{2}$$

Where D_i is the internal pipe diameter, determined from geometric measurement [10].

2.2 Reynolds Number

The Reynolds number (Re) is defined as:

$$Re = \frac{\rho v D_i}{\mu} \tag{3}$$

where ρ and μ are the density and dynamic viscosity of water, evaluated at approximately 23 °C. All experimental operating points considered in this study lie within the turbulent regime, which supports the applicability of both the ultrasonic and vortex flowmeter models [3,10]. The Re ranged from 19040 to 114245 for the ultrasonic flowmeter, and from 24296 to 145776 for the vortex flowmeter.

2.3 Electromagnetic Flowmeter as Reference Device

The electromagnetic flowmeter measures flow velocity according to Faraday's law of electromagnetic induction:

$$E = BLv \tag{4}$$

where E is the induced voltage, B the magnetic flux density, and L is the spacing between electrodes. Because of its direct proportionality to velocity and its relatively low sensitivity to velocity profile distortion, the electromagnetic flowmeter is used as a reference device in comparative flow experiments [8,14].

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2.4 Ultrasonic Transit-time Flowmeter

The ultrasonic transit-time flowmeter determines velocity (v_{US}) from the difference between downstream and upstream acoustic transit times:

$$v_{US} = \frac{L}{2cos\theta}\left(\frac{1}{t_{up}} - \frac{1}{t_{down}}\right) \tag{5}$$

where L is the acoustic path length and θ is the acoustic inclination angle. At low velocities, the transit-time difference $\Delta t = t_{\text{up}} - t_{\text{down}}$ becomes small, leading to a rapid increase in relative uncertainty. This behavior represents a fundamental limitation of the transit-time method and has been reported in the literature [1,6].

2.5 Vortex Flowmeter

Vortex flowmeters operate on the principle of periodic vortex shedding from a bluff body. The vortex shedding frequency f is related to flow velocity (v_{vortex}) through the Strouhal number (*St*):

$$St = \frac{fD}{v} \Rightarrow v_{vortex} = \frac{fD}{St} \tag{6}$$

For typical industrial bluff body geometries, the Strouhal number remains approximately constant over a broad range of Reynolds numbers, resulting in an approximately linear relationship between vortex shedding frequency and flow velocity [3,5,13].

3. Uncertainty Analysis

Uncertainty in this study was evaluated according to the ISO/IEC Guide to the Expression of Uncertainty in Measurement (ISO-GUM) [7]. For each method, velocity was defined as the measurand and written as a function of the relevant independent input quantities. Standard uncertainties were propagated through the measurement models using the law of propagation of uncertainty, and the expanded uncertainty was calculated with a coverage factor of $k = 2$, corresponding to approximately 95% confidence.

3.1 Theoretical Velocity Uncertainty

Following ISO-GUM [7], the relative standard uncertainty of the theoretical velocity can be expressed as:

$$\frac{u(v_{\text{th}})}{v_{\text{th}}} = \sqrt{\left(\frac{u(Q)}{Q}\right)^2 + \left(2\,\frac{u(D)}{D}\right)^2} \tag{7}$$

Because the pipe diameter (D) enters the velocity model quadratically, its uncertainty makes a dominant contribution to the overall uncertainty budget, in agreement with established metrological practice [10].

3.2 Ultrasonic Flowmeter Uncertainty

For ultrasonic transit-time flowmeters, the relative uncertainty may be approximated as:

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$$\frac{u(v_{\mathrm{US}})}{v_{\mathrm{US}}} \approx \frac{u(\Delta t)}{\Delta t} + \frac{u(\theta)}{\tan\theta} \tag{8}$$

As $\Delta t \to 0$ at low velocities, the relative uncertainty increases significantly, which explains the larger deviations observed experimentally in the low velocity region [1,2,6].

3.3 Vortex Flowmeter Uncertainty

For vortex flowmeters, uncertainty propagation:

$$\frac{u(v_{\mathrm{vortex}})}{v_{\mathrm{vortex}}} = \sqrt{\left(\frac{u(f)}{f}\right)^2 + \left(\frac{u(D)}{D}\right)^2 + \left(\frac{u(\mathrm{St})}{\mathrm{St}}\right)^2} \tag{9}$$

Under turbulent flow conditions (Re > 4000), variations in the Strouhal number are negligible, and the uncertainty is governed mainly by the frequency resolution [5,9].

3.4 Expanded Uncertainty

The expanded uncertainty (*U*) is defined as:

$$U = ku, \tag{10}$$

for k = 2.

3.5 Numerical Uncertainty Budgets

The uncertainty budgets in Tables 1 to 3 highlight the differences in measurement principle and uncertainty model for each method of velocity determination. Consequently, the number of contributing quantities and their relative importance are not the same for all three methods. The results show that the uncertainty of the theoretical velocity is influenced mainly by the inner pipe diameter. In the case of the ultrasonic flowmeter, the uncertainty increases noticeably at low flow rates (±12.4 % and ± 3% for high flow rates) as the transit-time difference becomes smaller. By contrast, the vortex flowmeter shows constant uncertainty (±2.4 %).

Table 1.

Uncertainty budget for theoretical velocity

Quantity	**Standard Uncertainty**	**Contribution [%]**
Volumetric flow rate *Q*	0.2%	0.2
Inner diameter *D*	0.5%	1.0
Combined standard uncertainty	-	1.02
Expanded uncertainty (k = 2)	-	±2.0

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Table 2.

Uncertainty budget for ultrasonic transit-time flowmeter

Source	**Contribution [%]**
Transit-time difference Δt	6.0 (1.0 at high velocity)
Acoustic angle θ	1.0
Pipe wall thickness	0.8
Signal noise / repeatability	0.7
Combined standard uncertainty	6.2
Expanded uncertainty (k = 2)	±12.4 (low velocity)

Table 3.

Uncertainty budget for vortex flowmeter

Source	**Contribution [%]**
Vortex frequency f	0.7
Inner diameter D	0.6
Strouhal number St	0.5
Signal processing	0.6
Combined standard uncertainty	1.2
Expanded uncertainty (k = 2)	±2.4

4. Experimental Setup and Results

The experiments are carried out on a DCS experimental platform under controlled conditions representative of an industrial environment. Water serves as the working fluid, with an average temperature of 23 °C, a density of 998 kg/m³, and an absolute in-line pressure of approximately 110 kPa. A centrifugal pump recirculates the water within the system, while a control valve regulates the flow rate. Three flowmeters are installed in series: a clamp-on ultrasonic flowmeter Flexim FLUXUS F601 (on a main pipeline with inner diameter of 99.4 mm), an in-line vortex flowmeter Rosemount 8800D (with a measuring tube inner diameter of 77.9 mm), and an electromagnetic flowmeter ABB 50XM2000 (with a measuring tube inner diameter of 98 mm), which serves as the reference device. The experimental procedure follows established practice for the comparative evaluation of industrial flowmeters [8,10].

Figure 1 illustrates the recorded flow profile from the reference electromagnetic flowmeter FT-1 (blue), the vortex flowmeter FT-2 (green), and the ultrasonic transit-time flowmeter FT-3 (red). The regulated flow was increased stepwise and maintained at successive steady operating levels, allowing comparison of both the dynamic response and the steady state behavior of the tested devices.

Both the vortex and ultrasonic flowmeters followed FT-1 output signal closely throughout the experimental procedure, demonstrating consistent response to the regulated flow variations. The minor discrepancies visible during transient intervals are consistent with differences in measurement principle and internal signal processing. The rapid flow reduction at the end of the test provides an additional indication of transient performance and shows that all flowmeters operated without observable saturation or hysteresis over the investigated range.

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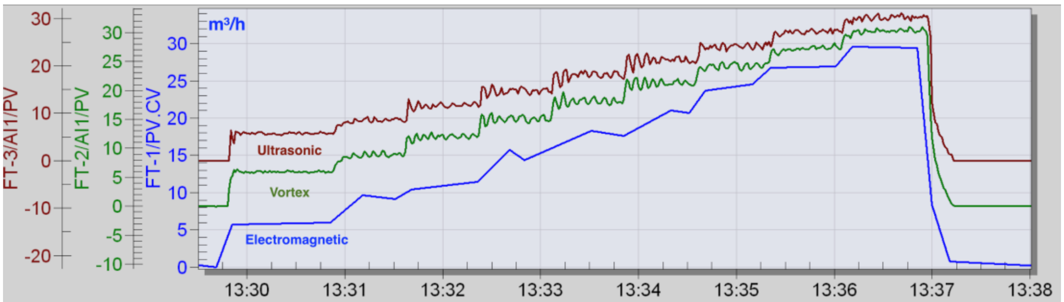

Fig. 1. Flow profile during experimental testing

4.1 Ultrasonic Flowmeter Results

At low velocities, at approximately 0.18–0.25 m/s, the ultrasonic flowmeter shows deviations reaching −7%, indicating systematic under reading relative to the reference (Fig. 2). With increasing velocity, the deviation decreases rapidly and remains within approximately ±1% above 0.4 m/s. Beyond that, at about 0.6 m/s, the deviations appear randomly distributed around zero, with no clear systematic trend. This behavior reflects the fundamental limitation of the transit-time method at low velocities, where the transit-time difference becomes too small and the relative effect of timing uncertainty increases. At higher flow rates (>12 m^3/h), the larger transit-time difference improves measurement stability, and the observed deviations remain within the expected uncertainty range. Relative to the expanded uncertainty of the ultrasonic flowmeter (±12.5% at velocities < 0.4 m/s and ±3% for velocities > 0.4 m/s), all of the results lie within the uncertainty bands.

Table 4.

Ultrasonic flowmeter results

Flow rate [m³/h]	Velocity calculated [m/s]	Reynolds number [Re]	Velocity measured [m/s]
5	0,17898	19040	0,17
10	0,35796	38081	0,36
11	0,393756	41890	0,4
12	0,429552	45698	0,43
13	0,465348	49506	0,47
14	0,501144	53314	0,5
15	0,53694	57122	0,53
20	0,715921	76163	0,71
25	0,894901	95204	0,9
26	0,930697	99012	0,93
27	0,966493	102821	0,97
28	1,002289	106629	1,00
29	1,038085	110437	1,04
30	1,073881	114245	1,07

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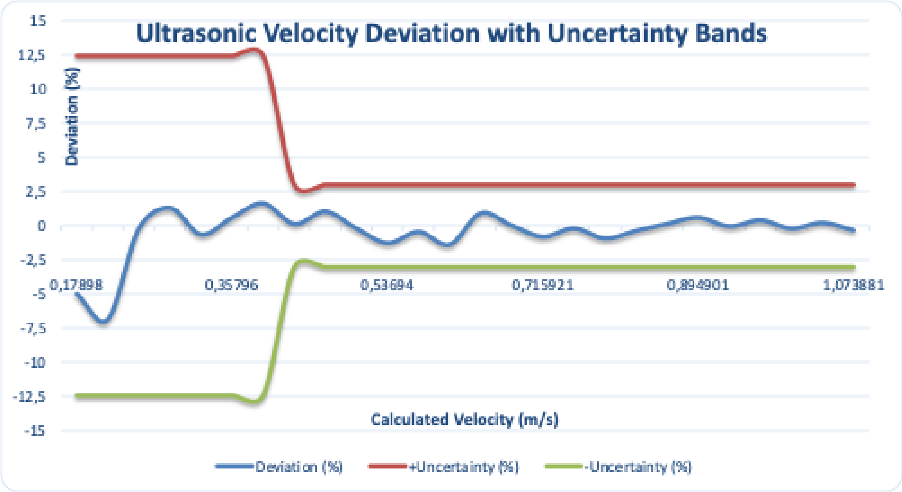

Fig. 2. Relative deviation of FLEXUS F601 velocity. Expanded uncertainty bands correspond to ±12.4% at low velocity and ±3% in fully turbulent flow

4.2 Vortex Flowmeter Results

The vortex flowmeter measurements spanned velocities from 0.29 m/s to 1.76 m/s. Within this range, the vortex shedding frequency increased linearly from 3.93 Hz to 23.94 Hz (Fig. 3), without evidence of saturation or hysteresis, indicating consistent shedding behavior [3,4]. The deviations were generally confined to between approximately −3.5% and +5.5%. Slightly larger deviations at velocities below 0.75 m/s are attributed to the onset of vortex shedding, where the shedding process is not yet fully periodic (Fig. 4). Above approximately 1.4 m/s, the deviations stabilize and fluctuate randomly near zero, consistent with fully developed vortex shedding. Relative to the expanded uncertainty of the vortex flowmeter (±2.4%), most results lie within or near the uncertainty limits. The small number of points outside these bounds can be explained by frequency resolution and signal processing effects rather than by systematic bias.

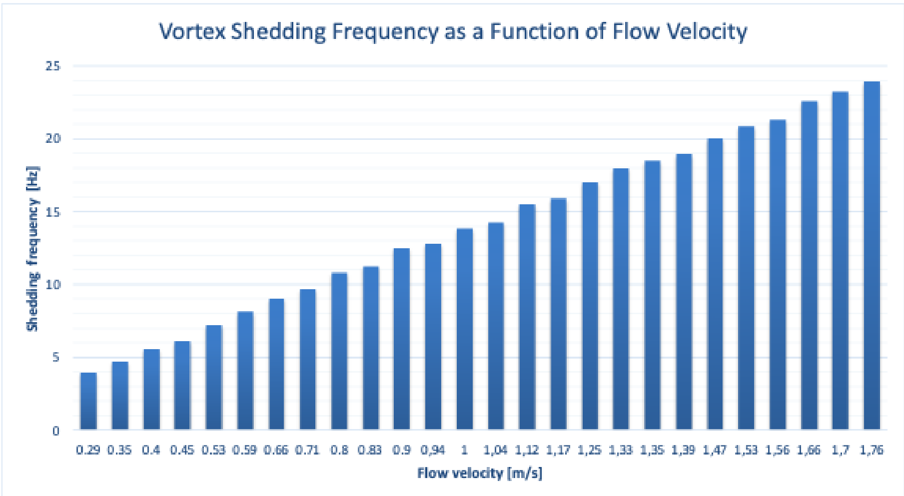

Fig. 1. Linear relationship between measured vortex shedding frequency and flow velocity

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Table 5.

Vortex flowmeter results

Flow rate [m³/h]	**Velocity calculated [m/s]**	**Reynolds number [Re]**	**Velocity measured [m/s]**	**Frequency measured [Hz]**
5	0,291409	24296	0,29	3,93
10	0,582818	48592	0,59	8,1
11	0,641099	53451	0,66	9
12	0,699381	58310	0,71	9,65
13	0,757663	63169	0,8	10,81
14	0,815945	68029	0,83	11,26
15	0,874226	72888	0,9	12,5
20	1,165635	97184	1,17	15,88
25	1,457044	121480	1,47	20,04
26	1,515326	126339	1,53	20,85
27	1,573608	131199	1,56	21,3
28	1,631889	136058	1,66	22,6
29	1,690171	140917	1,7	23,2
30	1,748453	145776	1,76	23,94

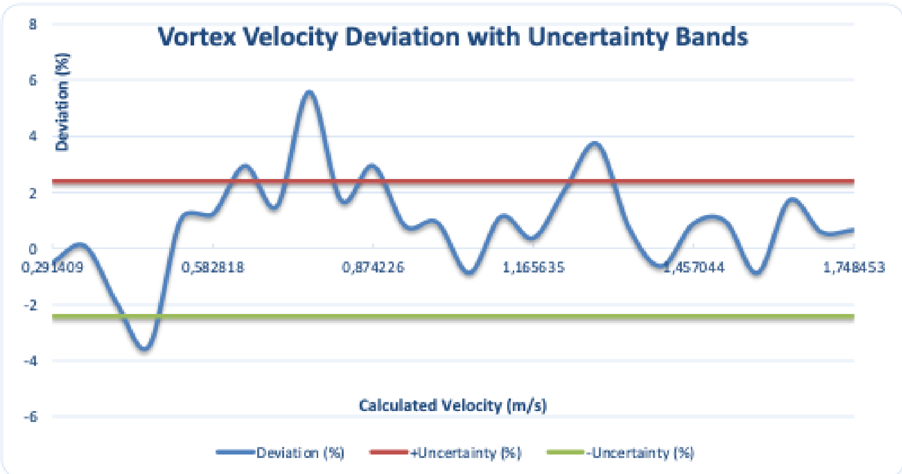

Fig. 2. Relative deviation of 8800D velocity. Expanded uncertainty band corresponds to ±2.4%

5. Conclusion

This study confirms a good level of agreement between the theoretically derived flow rate values and the experimentally measured values from FLEXUS F601 and Rosemount 8800D. Comparing them within the defined uncertainty models according to ISO-GUM [7]. This consistency over the range of flow investigations supports the validity of the applied measurement approaches.

An important result of the analysis is the pronounced difference in the sources of uncertainty for each measurement method. The theoretical flow rate is largely influenced by the uncertainty in the measuring tube diameter. In contrast, the ultrasonic flow meter is particularly sensitive to the transit-time differences, especially at low flow rates, where Δt is relatively

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small. As a result, larger relative deviations are observed in this range, although it remains within the uncertainty limits.

The analysis of the vortex flowmeter results indicates that only at flow velocities above 1.4 m/s do the deviations fall within the limits of the uncertainty model and fluctuate around zero. Under these conditions, the deviations become largely independent of flow velocity, confirming the suitability of this method for applications involving fully developed turbulent flow and Re above 111000 under the given operational condtions.

In conclusion, the observed differences between the measurement methods are primarily attributed to their underlying measurement principles rather than to systematic errors. Both devices can therefore be considered reliable within the investigated operating ranges.

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