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Pipeline Flow Measurement Technologies, Accuracy Influencing Factors, and Engineering Selection Criteria

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Abstract. Accurate pipeline flow measurement is essential for urban water supply, petroleum transportation, leakage detection, and industrial process control. This paper examines the operating principles, performance characteristics, major error sources, and application suitability of commonly used pipeline flowmeters. Differential-pressure devices, including Venturi meters, orifice plates, and Pitot tubes, are compared with ultrasonic, electromagnetic, turbine, and Coriolis flowmeters. Their measurement principles, pressure loss, accuracy, installation requirements, applicable fluids, maintenance demands, and cost characteristics are discussed. Particular attention is given to factors affecting measurement accuracy, including Reynolds number, velocity-profile distortion, upstream disturbances caused by bends and valves, insufficient straight-pipe length, fluid density and viscosity, temperature and pressure variations, calibration errors, zero drift, and signal-processing effects. The paper also distinguishes systematic and random errors and discusses uncertainty propagation in flow calculations. Application-oriented comparisons show that no single flowmeter is suitable for all conditions. Instrument selection therefore requires a compromise among accuracy, pressure loss, fluid properties, installation constraints, operating range, and cost. Future improvements should focus on realistic-condition calibration, real-time compensation, and intelligent correction of flow-profile disturbances.

Keywords: Pipeline flow measurement, Flowmeters, Measurement accuracy, Uncertainty analysis, Instrument selection

1. Introduction

Accurate flow measurement is essential in many industries and urban infrastructure, including city water supply, petroleum transportation, and chemical batching systems. In these practical applications, ideal situations rarely exist, and errors can be introduced by bends, valves, or changes in fluid properties; these inaccuracies may lead to significant financial losses, reductions in efficiency, and safety hazards. For example, in water distribution networks, errors can affect leak detection, as flow readings of supply and consumption are often compared to provide data for detection. Moreover, in petroleum transfer, a small inaccuracy can lead to significant financial loss.

To address this challenge, a wide range of flow measurement techniques with different advantages have been introduced for different practical situations. These can be roughly classified into differential-pressure devices, including the Venturi meter, the orifice plate, and the Pitot tube;

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and non-differential-pressure devices, including the ultrasonic flowmeter, the electromagnetic flowmeter, the turbine flowmeter, and the Coriolis flowmeter. Each method has its own focus and limitations, and the final choice often takes into account multiple factors, including accuracy, cost, pressure loss, and maintenance.

The development of flow measurement has been one of the important focuses in applied physics since the 18th century. Differential-pressure methods were first widely accepted because they rely mainly on pressure measurements and known pipe geometry, and the theoretical basis of differential-pressure methods dates back to Bernoulli's work in the 18th century. Other non-differential-pressure methods became increasingly common following the development of electronics and sensors in the 20th century. However, despite these advances, differential-pressure-based instruments remain considerably common in practice today, and the main reason is that they offer higher reliability under high pressure and temperature.

This paper reviews the main pipe-flow measurement techniques and the factors affecting their accuracy. We will first introduce the fundamental fluid mechanics concepts of pipe flow in Section 2. Then, Section 3 focuses on three common types of differential-pressure flowmeters: the Venturi meter, the orifice plate, and the Pitot tube; a brief comparison of their advantages and limitations is also included. The following Section 4 introduces four non-differential-pressure flowmeters: the ultrasonic flowmeter, the electromagnetic flowmeter, the turbine flowmeter, and the Coriolis flowmeter. Section 5 focuses on the factors affecting measurement accuracy, including the flow regime and velocity profile effects, disturbances, required straight pipe lengths, fluid properties, and instrument factors. Section 6 further discusses expressions and types of errors, and uncertainty propagation. Finally, Section 7 discusses the performance of the methods under different practical conditions.

2. Fundamental principles of pipeline flow measurement

2.1. Volumetric flow rate

Volumetric flow rate Q is defined as:

$$Q = A \cdot \bar{v} \tag{1}$$

where A is the cross-sectional area of the pipe, and $\bar{v}$ is the average velocity.

Since for a given pipe A is constant, measuring Q is equivalent to measuring the average velocity. This approach is used by all flowmeters discussed in later sections.

2.2. Continuity equation

For incompressible fluids, the continuity equation states that the volumetric flow rate remains constant:

$$Q_1 = Q_2 \tag{2}$$

or:

$$A_1 \cdot \bar{v}_1 = A_2 \cdot \bar{v}_2 \tag{3}$$

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When combined with the Bernoulli equation, the change in velocity can be related to the pressure difference. This principle is the basis of Venturi meters and orifice plates.

2.3. Bernoulli equation

For incompressible, inviscid, steady flow, the simplified form of the Bernoulli equation states the relation between pressure and velocity:

$$\mathrm{p} + \tfrac{1}{2}\rho \mathrm{v}^2 = \text{constant} \tag{4}$$

From this equation:

$$\mathrm{p} \propto \mathrm{v}^2 \tag{5}$$

or more precisely:

$$\mathrm{v} = \sqrt{\frac{2\Delta \mathrm{p}}{\rho}} \tag{6}$$

Therefore, pressure difference can be used to determine velocity. As mentioned above, this method is used by Venturi meters and orifice plates. For Pitot tubes, the dynamic pressure is calculated as the difference between stagnation pressure and static pressure, and the local velocity can be determined.

2.4. Reynolds number

The Reynolds number Re is defined as:

$$\mathrm{Re} = \frac{\rho \mathrm{v} \mathrm{D}}{\mu} \tag{7}$$

where ρ is the density of the fluid, v is the velocity, D is the diameter of the pipe, and μ is the dynamic viscosity.

The Reynolds number is used to determine the discharge coefficient. In practice, viscosity must be considered to reduce inaccuracy, and the discharge coefficient is therefore introduced to take the energy losses caused by fluid viscosity into account. Flowmeters often specify a valid Re range within which the error is acceptable. In addition, the Reynolds number provides information about the velocity profile, as explained below.

2.5. Velocity profile

The velocity profile describes the distribution of velocity across the pipe cross-section. Generally, the velocity is zero close to the walls and increases towards the center. More specifically, in laminar flow, the parabolic velocity distribution means that the average velocity is half of the centre velocity. For turbulent flow, the difference is considerably smaller, as the velocity distribution is fatter.

This affects the accuracy of flowmeters that are sensitive to velocity distribution. For example, for Pitot tubes, knowing the velocity profile allows the average velocity to be estimated through pointwise velocity.

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Additionally, installations near bends or valves disturb the profile and cause errors, as the flowmeters are calibrated under fully developed flow conditions. Further explanations are given in Section 5.

3. Differential-pressure flow measurement techniques

3.1. Differential pressure flowmeters

For differential pressure flowmeters, Bernoulli's principle is the common foundation. According to the principle, the flow velocity can be calculated by:

$$v = \sqrt{\frac{2\Delta p}{\rho}} \tag{8}$$

Therefore, measuring the pressure difference can determine velocity.

Based on the equation, the general construction of the differential pressure flowmeter usually contains a constriction in the pipe. In the constriction, fluid velocity increases, and its static pressure decreases. The pressure difference can be obtained from the difference between two positions, and the velocity can be estimated.

However, as introduced below, each device applies this principle differently, leading to unique advantages and limitations in real-life applications.

3.2. Venturi meter

Venturi meter is a type of differential pressure flow meter that contains a converging section, a throat, and a diverging section. It determines the velocity by the pressure difference between the entrance and the throat.

As cross-sectional area decreases from the converging section to the throat, pressure decreases. The pressure differences are obtained by measuring pressure at the entrance in the converging section and at the throat. Venturi meter then calculates the overall average velocity, adding a discharge coefficient reaching approximately 0.99 to reduce errors. In the diverging section, the cross-sectional area increases, leading to a pressure recovery stage, reducing energy loss [1].

Venturi meters are accepted in applications that require accuracy and energy efficiency. Based on pressure recovery, they allow favourable energy efficiency. In addition, Venturi meters have a smooth internal structure, reducing disturbances and leading to high accuracy and repeatability.

However, the high manufacturing and installation cost of Venturi meters limits their applications. Moreover, the large installation space and the need for regular calibrations are often discouragements for consumers.

3.3. Orifice plate

Orifice plates are differential flowmeters that are made up of two thin metal plates with a precisely machined hole in the centre. They measure velocity by the pressure difference between the upstream and downstream sides.

As fluid passes through, the pressure drops with rapid acceleration. This forms a vena contracta, with the lowest cross-sectional area and minimum pressure. The pressure difference is obtained by measuring upstream and downstream pressure, and velocity is estimated. Like Venturi meters, a discharge coefficient of around 0.92-0.99 is added to calculations.

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Orifice plates are widely applied in industries with financial and practical requirements. The construction is simple: the two metal plates are clamped between two flanges and are easy to install or replace. The manufacturing cost is relatively low, and the high standard of the equipment minimises the need for calibration.

However, because of sudden acceleration, the pressure loss is considerably high, and significant disturbances occur, leading to higher inaccuracy. Additionally, the questionable durability is also a consideration for firms [2].

3.4. Pitot tube

Pitot tubes are differential pressure flowmeters containing a stagnation pressure tube in the direction perpendicular to and facing the flow, a static port, and a differential pressure sensor. They obtain the local pointwise velocity through the dynamic pressure.

The flow decelerates to zero at the stagnation pressure tube, allowing the tube to measure the stagnation pressure P_0. Moreover, the static port measures the static pressure. P of the undisturbed fluid. According to Bernoulli's equation:

$$P_0 - P = \frac{1}{2}\rho v^2 \tag{9}$$

Thus, the local velocity can be determined:

$$v = \sqrt{\frac{2(P_0 - P)}{\rho}} \tag{10}$$

The features of the Pitot tube, including low manufacturing cost, negligible pressure loss, simple construction and pointwise velocity measurements, allow it to be applied in specialised fields where high sensitivity to pressure loss, the need for velocity distribution measurements, or considerably large pipe diameters occur.

However, pointwise velocity measurements indicate that it is sensitive to velocity distribution. Moreover, to obtain overall average velocity, one must either measure velocities at multiple points and integrate them across the pipe area, or use an averaging Pitot tube that has multiple sensing ports.

4. Non-differential-pressure flow measurement techniques

4.1. Other flowmeters

The differential pressure flowmeters discussed in the previous section rely on Bernoulli's equation and determine flow velocity by obtaining pressure difference. However, in practical use, requirements including no pressure loss, corrosive fluids or high purity, and mass measurements demand varying measurement means. The following flowmeters introduced are based on fundamentally different physical principles, each with specific requirements, advantages, and limitations, making them suitable for different types of fluids and operating conditions.

4.2. Ultrasonic flowmeters

By working principles, ultrasonic flowmeters are often classified into two types: the transit-time flowmeters and the Doppler flowmeters.

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In the transit-time method, transducers are set at upstream and downstream, alternatively sending ultrasonic signals in the flow direction and the opposite direction. The travelling velocity of the two ultrasonic waves differs because of flow velocity, and the time difference obtained is directly proportional to the fluid velocity. The transit-time flowmeters require high fluid purity, avoiding scattering and absorption.

In the Doppler method, transducers emit ultrasonic waves which are then reflected by scatterers in the fluid (including particles and bubbles). Based on the Doppler effect, the reflected wave has a different frequency due to flow velocity, and the difference is obtained to estimate velocity. As scatterers are required, the Doppler method is not suitable for fluids with high purity.

As it is often non-invasive, ultrasonic flowmeters are widely applied in facilities where extra loss of pressure is unacceptable, and disturbances must be minimised. Additionally, the maintenance cost is low, and bidirectional measurements can be taken.However, as mentioned, they are sensitive to flow profile, and their operating principles indicate high requirements for the sound conductivity of pipe materials [3].

4.3. Electromagnetic flowmeter

The fundamental operation principle of the electromagnetic flowmeter is Faraday's law of electromagnetic induction. As a conductive fluid passes through the coils of the flowmeter, which generate a magnetic field, a voltage is induced. Qualitatively, this can be simplified as:

$$U = k \cdot B \cdot D \cdot v \tag{11}$$

Where k is a constant, U is the induced voltage, B is the magnetic field intensity, D is the pipe diameter, and v is the flow velocity.

Therefore, as the electrodes in the flowmeter measure the induced voltage, the flow velocity can be obtained.

Since it measures the induced voltage, the velocity obtained from the electromagnetic flowmeter is independent of fluid density and viscosity; thus, the flowmeter is suitable for contaminated fluids. Moreover, the flowmeter allows no additional pressure loss, as it contains no obstructive or moving parts in the fluid.

However, the limitations are obvious: The electromagnetic flowmeters cannot be applied to non-conductive fluids, and they require full pipes for high accuracy. Practically, the manufacturing cost is relatively unfavourable [4, 5].

4.4. Turbine flowmeter

Turbine flowmeters depend on mechanical motion: as the fluid passes through, it impinges and drives the blades of the rotor in the flowmeter, leading to rotation. The fluid velocity is directly proportional to the rotational velocity, and thus the flow velocity can be determined by the rotational velocity measured by sensors in the flowmeter.

The turbine flowmeter is often used in applications where accuracy and cost are both considerations [6]. Since it often measures rotational velocity by converting rotation into electrical pulses and digital output, the accuracy and repeatability are relatively higher than analogue measurements. Practically, the moderate cost is acceptable for most industries.

However, as it relies on mechanically moving parts, the questionable durability is one of the discouragements for consumers. The mechanical operation also indicates pressure drop and high

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sensitivity to viscosity; thus, it is not applicable for unclean fluids. As can be inferred from its working principle, it also requires a full pipe.

4.5. Coriolis flowmeter

Coriolis flowmeter directly measures the mass flow rate instead of the volumetric flow rate. The basic process can be described as follows: the flowmeter contains a vibrating tube. As fluid passes through, the Coriolis force results in a twist of the fluid, which is measured as a phase shift and is directly proportional to the mass flow rate. Therefore, the mass flow rate can be determined.

For certain types of Coriolis flowmeters, density can be obtained simultaneously. To achieve this, the natural vibration frequency of the tube is constantly measured, and through continuous comparison with the calibration, real-time density can be obtained.Coriolis flowmeter provides high accuracy and allows bidirectional measurements and simultaneous density measurements. As it is based on the Coriolis force, the measurements are independent of temperature, pressure, and fluid properties.

However, the cost is significantly higher than other flowmeters, and the pressure drop is unacceptable. The durability is highly affected by abrasive liquids; thus, the application depends on the particles in the fluid [7, 8].

5. Factors affecting flow measurement accuracy

5.1. Flow regime and velocity profile

Most flowmeters are calibrated under fully developed flow conditions, where the velocity profile is stable and symmetric. In practice, however, there exist differences between the actual profile and calibration conditions, and this variation is a major source of error.

Distortions in the velocity profile will cause the measured pressure difference to be unrepresentative of the average velocity. Based on this property, orifice plates, due to sudden contraction, have the highest sensitivity to the velocity profile. Meanwhile, the main error source for pitot tubes is the low representativeness of the local pointwise velocity.

For other flowmeters, turbine flowmeters show invalid measurements as the distortions alter the angle of attack on the blades, and ultrasonic transit-time flowmeters may be inapplicable as the path velocity may be unequal to the average velocity.

5.2. Disturbances from bends, valves, and fittings

Other than natural disturbances caused by flow regime, pipe components including bends, valves and fittings also disturb the flow and distort the velocity profile.

A common example is bends in pipes: as they force flow to change direction, creating a velocity difference, where velocity decreases from the inner region to the outer region. This further leads to a pressure difference, as pressure increases from the inner area to the outer area, the effect of centrifugal force decreases. Thus, separated inner and outer vortices are formed, resulting in secondary flow. Moreover, when two non-coplanar bends are constructed, a swirl is introduced, and the impact often requires a long distance to be eliminated.

Other pipe components have similar effects: partially closed valves cause flow separation and recirculation, T-junctions result in asymmetrical velocity distribution, and sudden contraction or expansion leads to unstable flow.

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Similar to the effects of velocity profile variation caused by the flow regime, disturbances from components affect differential pressure flowmeters, as there is a mismatch between the pressure difference measured and the actual average flow. Additionally, systematic errors may be introduced in the applications of orifice plates and ultrasonic transit-time meters for similar reasons as the flow-regime-dependent velocity profile [9].

5.3. Straight pipe lengths

As described above, disturbances can be introduced by multiple factors; therefore, straight pipe lengths are required to minimise the inaccuracy. As flow passes the straight pipe sections, disturbances gradually decay, allowing flowmeters to take accurate values. If the lengths are insufficient, disturbances will not decay sufficiently and will affect the measurements.

The lengths of the straight pipe sections are not universally determined: they are instead highly dependent on the sensitivity of flowmeters and disturbance types. As an example, orifice plates, ultrasonic transit-time and turbine flowmeters are relatively sensitive to velocity distribution and often require longer straight sections. In contrast, Venturi meters, electromagnetic and Coriolis flowmeters usually have lower requirements on length, as the converging sections of Venturi meters rectify flow to a certain extent, and the operation method of the latter two makes them less sensitive to velocity profile.

Moreover, types of disturbances similarly affect the lengths. For instance, disturbances caused by a single bend decay more rapidly, and swirls due to non-coplanar bends, instability from T-junctions and sudden contraction or expansion require a longer distance to eliminate.

In practice, standards of minimum straight pipe section lengths are often established depending on the flowmeters and situations (ISO 5167). Flow conditioners are often added as a solution to limited space; however, the effect is limited as they introduce pressure loss.

5.4. Fluid properties

Fluid properties are one of the major factors affecting the accuracy of flowmeters:

5.4.1. Density

For differential pressure flowmeters, as stated in the equation:

$$Q \propto \sqrt{\frac{\Delta P}{\rho}} \tag{12}$$

Density directly affects the measurements. Systematic errors will be introduced if the actual density differs from the calibrated value, and it is especially significant for gases.

As mass is directly obtained in practice, Coriolis flowmeters are less sensitive to density. However, if volumetric flow rate is needed, then density will influence the results.

5.4.2. Viscosity

Viscosity affects the Reynolds number, which determines the flow regime. Thus, if viscosity differs from the set value, flow may go from laminar to turbulent, and the velocity profile changes; therefore, flowmeter calibration becomes invalid.

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This occurs in most applications: for differential pressure flowmeters, a change in velocity distribution often means the measured pressure difference is not representative; and for turbine flowmeters, it affects the resistance force on the blades. The original calibration is inapplicable and results in relatively significant errors.

5.4.3. Electrical conductivity

Electromagnetic flowmeters require the fluid to have sufficient electrical conductivity. Therefore, it is necessary that the fluid measured has a certain degree of conductivity.

5.4.4. Gas and particle content

Gas and particle contents affect the flowmeters in various ways. Excess contents may cause saturation of signals for the Doppler ultrasonic flowmeters. Coriolis flowmeters are sensitive to two-phase flow, and large particles may lower the durability of turbine flowmeters.

5.4.5. Temperature and pressure

Temperature and pressure affect various factors, including density (especially for gases), viscosity, pipe dimensions, and the performance of electronic components. Thus, temperature and pressure compensation is required for most flowmeters.

5.5. Instrumental errors

Instrumental errors arise from the features and the installation of the flowmeters, and introduce inaccuracy to measurements even under ideal flow fields and fluid properties:

As the calibrations of flowmeters are often performed under ideal laboratory conditions, variations in practical installation may introduce systematic errors and cause invalidations of calibration curves. This especially affects the performance of differential pressure flowmeters and turbine flowmeters, as they rely on empirical coefficients C_d.

Limitations of resolution result in random errors in measurements. The effect is especially significant in situations where the flow rate is slow, and large relative errors can occur. Differential pressure flowmeters are especially affected when the pressure difference is small.

In some applications, the flowmeters produce a non-zero output even at no flow, and constant offsets are added to all the readings. This may be caused by installation stress, limited durability of sensors, and temperature excursion of electronic components. Electromagnetic and Coriolis flowmeters are particularly affected by zero drifts.

The outputs of flowmeters are analogue signals (except turbine flowmeters) and require sampling and filtering. This process may affect the accuracy, as insufficient sampling rates cause loss of information on rapid changes, and excessive filtering slows the response and may hide real variations. Sampling and signal processing is a source of errors in the applications of turbine flowmeters, ultrasonic flowmeters, and differential pressure flowmeters. Installation processes may introduce systematic errors, including reversed directions and incorrect positions. For electromagnetic flowmeters, proper grounding is particularly required.

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6. Measurement errors and uncertainty analysis

6.1. Absolute errors, relative errors, and repeatability

Errors are the differences between the measurements and the true value, and they can be expressed in absolute errors and relative errors.

Absolute errors express the differences as: $Measured\ value - True\ value$. And multiplied by a unit.

In contrast, the expression in relative errors is:

$$\frac{Measured\ value - True\ value}{True\ value} \times 100\% \tag{13}$$

In practice, errors of flowmeters are often expressed in relative errors for easier comparison between different magnitude orders.

Repeatability is another consideration when choosing measuring instruments. It describes the consistency of repeated measurements under the same conditions and affects the precision of data.

6.2. Systematic errors and random errors

By source, errors can be classified into systematic errors and random errors.

Systematic errors are consistent, predictable differences from the true value, often caused by calibration inaccuracy, incorrect installation, or environmental conditions.

Random errors, in contrast, are unpredictable variations in measurement results, and they are often caused by turbulence, electronic noise, or changing conditions.

6.3. Uncertainty propagation

Uncertainty is the interval in which the true value is expected to lie. As flow rate is not directly measured but calculated based on several values obtained, the uncertainty of each measurement is affects the result.

As an example, for differential pressure flowmeters:

$$Q \propto \sqrt{\frac{\Delta P}{\rho}} \cdot D^2 \tag{14}$$

Where Q is the flow rate, ΔP is the pressure difference, ρ is the density, and D is the pipe diameter.

The uncertainty of pressure measurement is propagated to ΔP and then Q, the uncertainty of density measurement directly affects Q, and the uncertainty of diameter is propagated to Q similarly.

Among uncertainties of different quantities, the effect on the result varies based on how the flow rate is obtained. For instance, in the differential pressure flowmeter equation above, the uncertainties of pressure difference and density measurements have a less significant effect on flow rate based on the square root, and the uncertainty of diameter measurement is amplified due to the square.

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7. Performance comparison and engineering selection of flowmeters

7.1. Selection criteria

In practical selections, multiple factors are considered, and compromises are made based on the priority of different requirements:

Fluid properties determine the maximum level of instrument sensitivity to certain features that is acceptable for applications. States of fluids, whether liquids or gases, decide how sensitive the instrument can be to density, pressure and temperature conditions. Conductivity determines whether electromagnetic flowmeters can be applied, and gas or particle contents affect the availability of ultrasonic flowmeters. Other factors are discussed above in 5.4.

Different flowmeters have different turndown ratios, indicating they have different ranges of appropriate flow quantity when measuring. For example, flow with large changes in quantity may require ultrasonic, electromagnetic or Coriolis flowmeters, while Pitot tubes are more suitable for situations where the change in quantity is small. Different practical applications may have different degrees of requirements on accuracy. For example, in trade settlements, high accuracy is needed as the data has direct and significant effects on capital. In contrast, process controls are often less sensitive to accuracy. Application scenarios with large flow quantity or limited pressure, including urban water supply systems or gravity flow systems, often require minimizing pressure loss. In contrast, situations with small flow quantity or high pressure often consider other factors more preferentially than minimising pressure loss.

Space available for flowmeters often determines the availability of flowmeters that require relatively larger installation space. Straight pipe sections affect the inaccuracy of different flowmeters with different sensitivity to velocity profiles, and whether clamp-on flowmeters are appropriate affects the installation of ultrasonic flowmeters. Where installation space is constrained, compact or truncated Venturi configurations may provide an alternative, although their geometry must be carefully selected because truncation and divergent angle affect pressure loss and measurement uncertainty [10].

Costs are one of the main considerations for firms and individuals. The initial costs, installation costs, maintenance costs, and calibration periods impact the final decisions.

7.2. Applications

7.2.1. Urban water supply

In urban water supply systems, the fluid, which is domestic water, is usually conductive. Moreover, the driving pressure provided by pumps is relatively limited, and the diameter of pipes is usually large, with a high flow rate.

Based on these features, in order to maintain consistency and lower maintenance costs, electromagnetic and ultrasonic flowmeters are widely used in urban water supply. Clamp-on ultrasonic meters are convenient for retrofitting existing pipes, but there are higher requirements for installation positions.

7.2.2. Leakage detection

Leakage detection often requires flow monitoring at different points. Together with mass balance and network analysis, abnormal differences between supplied and consumed flow can be identified.

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These pipe systems often have large quantities of flow with limited pressure. Moreover, specific situations like urban water supply may require large turndown ratio as minimum night flow measurements are crucial. To maintain consistency, ultrasonic and electromagnetic flowmeters are widely applied.

7.2.3. Industrial process control

In these applications, real-time measurements and high stability are often required. Therefore, based on the specific types of fluids, a wide range of flowmeters are applied: Coriolis flowmeters are used for direct mass measurements, turbine flowmeters are applied for clean fluids with low viscosity, electromagnetic flowmeters are suitable for conducting fluids or corrosive substances, and differential pressure flowmeters allow costs to be minimised.

7.2.4. Energy pipelines

Since associated with trade settlements, high accuracy is often needed in energy pipelines. The quantity of flow is usually large, with limited pressure supply. Moreover, gas flow measurement usually requires temperature and pressure compensation.

Therefore, ultrasonic meters are widely used in large-diameter oil and gas pipelines because they cause almost no pressure loss. Coriolis meters are used for high-accuracy mass flow measurement in trade settlement.

8. Conclusion

This paper has reviewed the fundamental principles, practical characteristics, and major error sources of mainstream flow measurement instruments. Volumetric flow measurement can determine the average velocity, and this is achieved through differential pressure, acoustic, electromagnetic, mechanical, or Coriolis operating principles. Each method offers distinct advantages and disadvantages: Venturi and orifice plates are cost-effective and standardised but suffer from pressure loss and sensitivity to velocity profile. Ultrasonic and electromagnetic flowmeters provide non-invasive measurement yet have strict requirements on fluid cleanliness or electrical conductivity. Turbine meters achieve high accuracy and acceptable cost but are limited by moving parts and poor tolerance of contaminated fluids. Coriolis meters offer high-accuracy mass flow measurement independent of fluid properties; however, they have significantly higher cost and non-negligible pressure drop.

A central finding of this review is that measurement accuracy is not only determined by the instrument itself. Flow regime, Reynolds number, upstream disturbances from pipe constructions, insufficient straight pipe lengths, fluid properties, and instrumental factors all contribute to systematic or random errors. Uncertainty propagation further indicates that errors in pressure, density, and diameter measurements are amplified or reduced depending on the flow equation, with diameter uncertainty being particularly significant in differential pressure methods due to the square.

In engineering practice, the selection of a flowmeter requires a compromise among accuracy, pressure loss, cost, installation conditions, and fluid properties. Urban water supply and leakage detection widely apply ultrasonic and electromagnetic meters for their low pressure loss and large turndown ratio, while energy pipelines prioritise ultrasonic and Coriolis meters for high accuracy. Industrial process control adopts a wider range of instruments depending on fluid type and cost constraints.

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Future work could focus on the development of calibration methods, improving instrumental performance in realistic installation conditions, focusing on real-time compensation for temperature and pressure variations, and applying machine learning to correct for flow profile distortions. As industrial and urban water systems demand higher accuracy and lower maintenance, hybrid or intelligent flow measurement solutions will become increasingly important.

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