A New Type of Flow Measurement Device

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Abstract

Flow measurement plays an important role in industrial production, process control and energy utilization. The steam flow is affected by the state of steam properties and the design of the steam flowmeter during the measurement process, resulting in low measurement accuracy. Based on the combined measurement method of differential pressure flowmeter and vortex flowmeter, an integrated flow measurement device that integrates averaging-velocity tube and piezoelectric vortex flowmeter is proposed in this paper. It combines the structural features and advantages of the two flowmeters scientifically. In this paper, the differential pressure transmitter is used to detect the pressure difference on both sides of the cylinder. Due to fluid vibration and piezoelectric effect, the probe in the device generates regular vibration. And combined with Digital Signal Processing (DSP) technology and automatic frequency band adjustment method, the flexibility and stability of frequency signal processing are improved. The measurement performance of the device was evaluated in this paper. The experimental results show that the absolute value of the relative error of the device is within 1.00% and 1.50% under the conditions of single-phase water and single-phase gas, respectively. The device can achieve dual-signal measurement, and it has the advantages of wide applicability, good stability and strong anti-interference, which will provide a new design idea for the measurement of saturated wet steam.

1. Introduction

Flow measurement is widely used in thermal power plants, petroleum, metallurgy, aviation, machinery and other fields. Steam is an important secondary clean energy, which is widely used in power plants, petrochemicals and other industrial production [1-2]. The steam used in the industrial field basically exists in the state of wet steam. As a special gas-liquid two-phase flow, saturated wet steam has unique and complex physical properties, which brings great difficulties to the accurate measurement of wet steam [3]. Therefore, improving the measurement level of saturated wet steam has become a technical problem that needs to be solved urgently. And its accurate measurement is of great significance for promoting energy saving and improving product quality.

The wet steam measurement will be affected by many factors, such as the influence of discrete droplets in wet steam on metering accuracy, impact and damage to equipment components at higher flow rates, etc. Many scholars have conducted preliminary research on the problems existing in wet steam measurement. Jesse Yoder summarizes the importance of steam metering, and analyses the difficulties in the measurement of seven different types of steam flowmeter adequately, such as differential pressure, vortex street, target type, and ultrasonic [4]. Among them, the differential pressure flow sensor is the most widely used, such as orifice plate and Venturi tube. Melikhov et al. proposed multiple models to simulate and verify the pressure drop change of steam passing through the SPS orifice [5]. Although the orifice flowmeter and venturi have a long history of application, they also have obvious shortcomings. Such as complicated installation and maintenance, large pressure loss, small range ratio and high operating costs. The sharp drop in accuracy after long-term use is the main disadvantage of orifice flowmeter, which affects the improvement and development of steam flow measurement accuracy. The measurement range of the Venturi tube is small, its delivery volume and delivery distance are limited, and the fluid scours and wears the throat seriously [6].

In the development of steam flow measurement, flow meters such as Annubar, float type and and averaging-velocity tube have also appeared. Due to the simple structure, low price and easy maintenance, the averaging-velocity tube is widely used in large-diameter flow measurement. It has no moving parts inside, and is minimally affected by the vibration of field equipment and pipelines. Adefila et al. measured and evaluated the flow parameters of wet CO_2 using an averaging-velocity tube with flow regulating wings and a Coriolis mass flowmeter [7-8]. Cui et al. analyse the influence of the air damper installed downstream of the averaging-velocity tube on the airflow measurement [9]. Dobrowolski et al. discuss the influence of the probe shape and structural characteristics of the averaging-velocity tube on the differential pressure signal [10]. It is resistant to high temperature and high pressure, and can measure a variety of media. The characteristics of the averaging-velocity tube flowmeter, such as small pressure loss, high precision, good repeatability, and large range ratio, provide a new choice for accurate measurement of steam flow.

In the 1960s, to satisfy the flow metering level of superheated steam, Japan's Yokogawa and the American Eastech Company each developed a vortex flowmeter. The characteristics of high temperature resistance, small pressure loss, simple structure, firm installation and wide range of vortex flowmeter make it widely used in steam measurement [11]. Westende et al. used the large eddy simulation theory to analyse the distribution of droplets and the deposition on the tube wall under the secondary flow of the annular-mist flow [12]. Xu et al. proposed a signal processing method based on the peak-to-peak standard deviation and used an electromagnetic vortex flowmeter (EVFM) to detect sodium liquid bubbles [13]. Srinivasan et al. studied and discussed the influence of a single piezoelectric vortex sensor and two piezoelectric vortex flowmeters on the steam measurement, and conducted an experimental evaluation of the two steam quality measurement methods [14].

In industrial production and transportation, wet steam often generates energy loss with the change of working conditions, which brings great difficulties to the accurate measurement of wet steam. Vortex flowmeters are suitable for small-diameter flow measurement, while averaging-velocity tube flowmeters are suitable for large-diameter flow measurement. They have great advantages in the measurement of wet steam, such as wide range of application media, simple structure, high reliability and accuracy. Therefore, an intelligent integrated flow measurement device is proposed in this paper based on the structural characteristics of the averaging-velocity tube and the vortex flowmeter. Through the intelligent design of the vortex signal acquisition and the selection of the differential pressure transmitter, the differential pressure signal and the frequency signal are obtained, and then the flow measurement is achieved. The performance of the flow measurement device is mainly evaluated in this paper through the experimental test of single-phase water/gas. The device has strong anti-interference and good reliability, which provides a certain theoretical basis for the realization of wet steam measurement.

2. Structure and theory of the flow measurement device

2.1 Basic structure of the flow measurement device

The internal structure of the flow measurement device includes a detection cylinder and a probe placed behind it. The device adopts the tube body of averaging-velocity tube as the detection cylinder. The detection cylinder is in the shape of a triangular column, as shown in Figure 1. The averaging velocity tube is a metal central control rod that traverses the diameter of the pipe. It has multiple pressure tapping holes on the upstream surface (for measuring total pressure), and one or more pressure tapping holes on the downstream surface (for measuring static pressure). The difference between the total pressure and the static pressure is measured by the differential pressure transmitter, as shown in positions 1 and 2 in Figure 2. The vortex frequency signal is obtained based on the Karman vortex principle and fluid oscillation. After the fluid passes through the detection cylinder, two rows of stable and regularly arranged vortices will alternately fall off behind it. And part of the kinetic energy of the fluid is converted into fluid vibration. The probe can sense the vibration of the fluid, as shown in position 3 in Figure 2. Its vibration frequency has a certain proportional relationship with the flow rate.

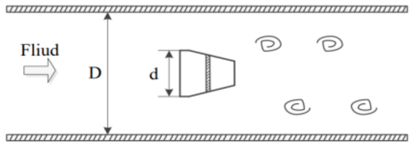

Figure 1: Schematic diagram of the principle of flow measurement device.

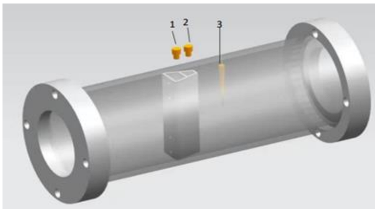

Figure 2: Schematic diagram of the two-way signal detection position of the flow measurement device.

2.2 Measurement theory

The theoretical model of the vortex flowmeter based on the principle of "Kaman vortex" is shown in Equation (1).

$$f = S_t \times \frac{v}{d} \tag{1}$$

Where f is the vortex shedding frequency, and v is the average flow rate on the side of the vortex generator. Where d is the width of the upstream surface of the vortex generator. Where St is the Strouhal number (dimensionless constant), and it can be kept as a constant value in a large range of Reynolds numbers. Since the size of the detection cylinder and the size of the pipe are fixed constants. There is a linear proportional relationship between frequency and flow rate.

The theoretical model of the integrated measurement device based on the vortex flowmeter and the averaging-velocity tube flow sensor is shown in Equation (2)-(6):

$$q_m = \frac{\rho_m f}{k_1} \tag{2}$$

$$f = \frac{k_1 q_m}{\rho_m} \tag{3}$$

Where q_m is the mass flow rate of the medium and ρ_m is the average density. Where k_1 is the meter coefficient of the vortex flowmeter after compensation and correction.

$$q_m = \varepsilon k_2 \sqrt{\Delta P \rho_m} \qquad (4)$$

$$\Delta P = \frac{{q_m}^2}{\varepsilon^2 {k_2}^2 \rho_m} \qquad (5)$$

$$q_m = \frac{\varepsilon^2 k_1 {k_2}^2 \Delta P}{f} \qquad (6)$$

Where ΔP is the average differential pressure output by the averaging-velocity tube, and k_2 is the flow coefficient of the averaging-velocity tube flowmeter after correction. Where ε is the expansion coefficient of the measured medium.

3. Experimental setup and testing

In this paper, the designed flow measurement device is experimentally tested by single-phase water and single-phase gas, and the performance of the device is evaluated.

3.1 Features of the Flow Measurement device

The flow measurement device can simultaneously measure the differential pressure signal of the averaging-velocity tube and the vortex shedding frequency signal of the vortex street. The parameter settings of the vortex flow sensor are shown in Table 1. The Digital Signal Processing (DSP) technology is adopted to replace the traditional analog filter with a digital filter. And the design of CPU can adjust and process in real time according to the sensor signal. It can automatically track and select the frequency band range of the filter according to the frequency of the signal, thereby greatly improving the flexibility, reliability and stability of signal processing. The physical diagrams of the device are shown in Figure 3.

Table 1: The specific parameter setting of the flow measuring device.

Device features	Specific parameters
Wide temperature range	-40 ℃~200 ℃
Analog/pulse output	4-20 mA
Supply voltage	24 VDC
Clear and intuitive display	Instantaneous flow rate, cumulative flow rate, flow rate, etc.
Communication method	HART/485
Adaptive digital signal processing	Digital Signal Processing (DSP)
Highly integrated	Parameter setting integration
Alarm output	Alarm output such as over-range, EEPROM error, etc.
Meter error compensation	Compensation with 5 segment approximate broken line

Figure 3: Physical diagram of the new type of flow measurement device.

3.2 Experimental test of single-phase water

In this paper, the water flow standard device is used to control and stabilize the actual flowrate. The range of measured flow rate is 1~15 m^3/h, the working pressure is 0.15~0.35 MPa, the working temperature is 25 ℃, and the test aperture is DN32. The diagram of the water flow standard device is shown in Figure 4.

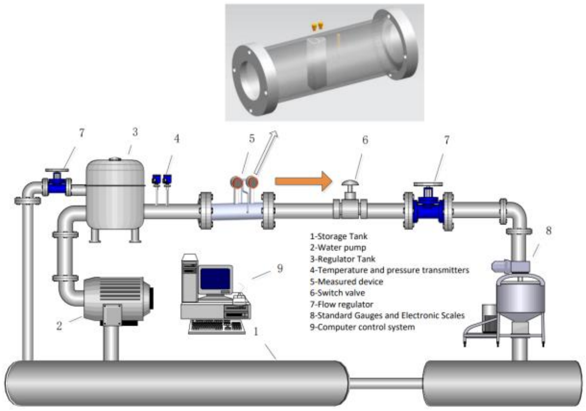

Figure 4: Schematic diagram of the water flow standard device.

In this paper, the gas flow standard device with sonic nozzle method is used to adjust and determine the actual flowrate. In this experiment, the range of measured flow rate is 15~100 m^3/h, the working temperature is 22 ℃, and the test aperture is DN32. The negative pressure method is selected as the measurement method. When the back-pressure ratio is less than 0.85, the airflow is in a stable state, and the experimental test can be carried out. The range of the differential pressure transmitter is set to 0-10 kPa. The diagram of the gas flow standard device with sonic nozzle method is shown in Figure 5.

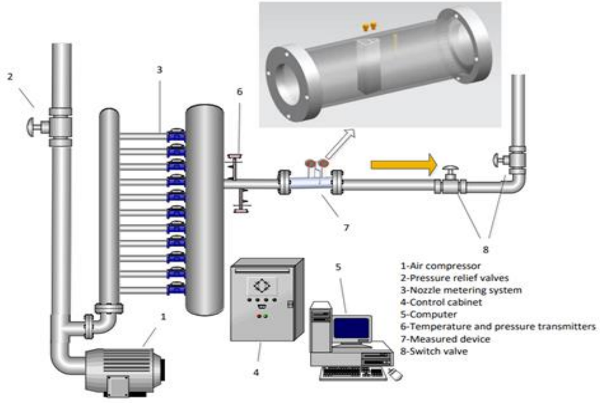

Figure 5: Schematic diagram of the working principle of the gas flow standard device of the sonic nozzle method.

4. Experimental results and analysis

4.1 Data processing and analysis of single-phase water

In this paper, the output signal of the device is repeatedly measured based on the following water flow points and water flow standard device: 1.02 m³/h, 1.94 m³/h, 3.06 m³/h, 4.02 m³/h, 4.996 m³/h, 6.01 m³/h, 7.05 m³/h, 8.06 m³/h, 9.00 m³/h, 10.01 m³/h, 11.02 m³/h, 12.00 m³/h, 12.948 m³/h, 13.892 m³/h and 15.053 m³/h. The relationship between the 13 flow points and the vortex frequency is linearly fitted, as shown in Figure 6.

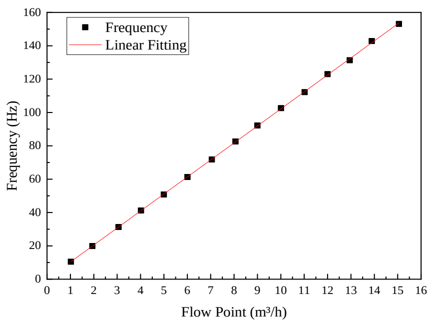

Figure 6: Linear fitting of water flow rate and vortex frequency.

The correlation coefficient of the fitting model is R^2=0.999, and the relationship between the frequency and the water flow rate is obtained as follows in Equation (7).

$$f_l = 10.202 \times q_{vl} \quad (7)$$

Where f_l is the vortex frequency of water, q_{vl} is Volume flow rate of water.

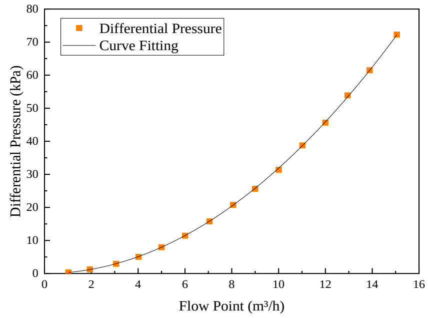

Figure 7: Curve fitting of water flow rate and differential pressure signal.

The differential pressure transmitter is used to collect the differential pressure signal from both sides of the detection cylinder. The range of the differential pressure transmitter is set to 0~100 kPa. Since the output mode of the differential pressure transmitter is a current output of 4-20 mA, the series resistance in the experiment is 250 Ω, and the output voltage is 1-5 v. A data acquisition card is used to collect the voltage signal and convert it into the corresponding differential pressure value. The mathematical relationship between the differential pressure signal and the water flow rate is shown in the Equation (8) and Figure 7.

$$\Delta P_l = 0.3185 \times {q_{vl}}^2 \quad (8)$$

Where ΔP_l is the differential pressure of water. The repeatability effect obtained by performing three repeatability experiments on two signals at each flow point is shown in Figure 8 and Figure 9.

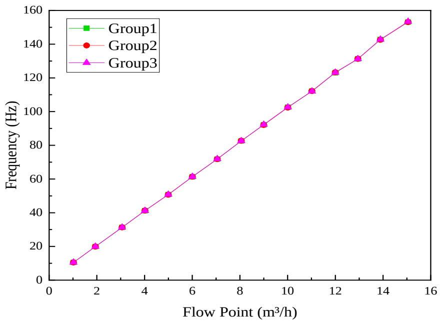

Figure 8: Effect diagram of single-phase water frequency signal under repetitive measurement.

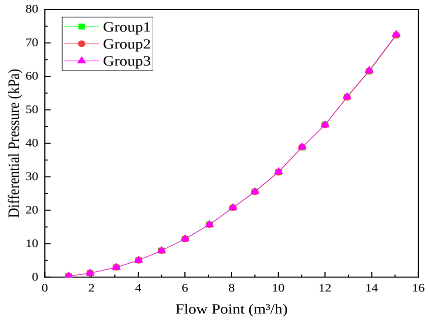

Figure 9: Effect diagram of single-phase water differential pressure signal under repetitive measurement.

In the single-phase water condition, the measurement errors of the differential pressure signal and the frequency signal are analysed, as shown in Fig. 10. The relative errors of the two signals are kept within ±1.00%.

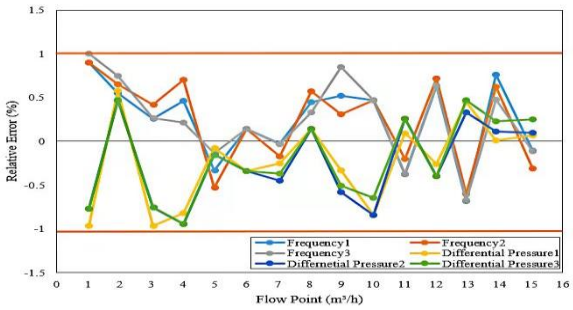

Figure 10: The relative error of the measurement of the two signals under different water flowrate points.

4.2 Data processing and analysis of single-phase gas

The output signal of the device is repeatedly measured based on the following gas flow rate: 15.6 m³/h, 20.2 m³/h, 30.1 m³/h, 40.2 m³/h, 50.4 m³/h, 59.9 m³/h, 70.1 m³/h, 80.7 m³/h, 90.2 m³/h, 101.3 m³/h, 112.1 m³/h, 121.9 m³/h, 130.8 m³/h and 142.9 m³/h. Vortex frequency and differential pressure are fitted linearly and curvilinearly to the 14 points respectively. And the correlation coefficients of the fitting models are all $R^2=0.999$, as shown in Figures 11 and 12.

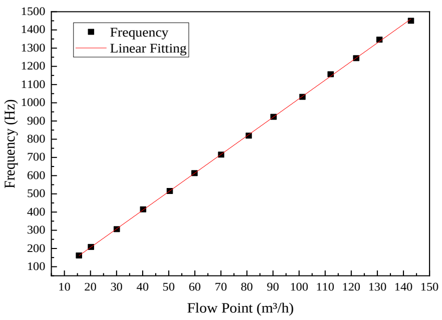

Figure 11: Linear fitting of gas flow rate and vortex frequency.

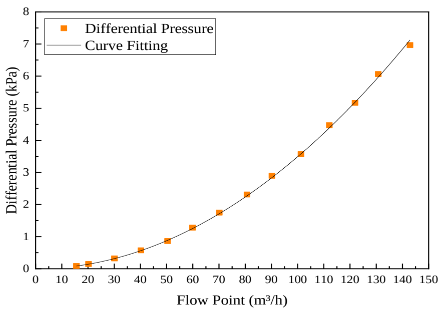

Figure 12: Curve fitting of gas flow rate and differential pressure signal.

The fitted relationships for frequency and gas flow rate, differential pressure and gas flow rate are shown in equation (9)-(10).

$$f_g = 10.213 \times q_{vg} \quad (9)$$

$$\Delta P_g = 3.49 \times 10^{-4} \times q_{vg}{}^2 \quad (10)$$

Where f_g is the vortex frequency of gas, q_{vg} is Volume flow rate, and ΔP_g is the differential pressure of water. The repeatability effect obtained by performing three repeatability experiments on two signals is shown in the Figure 13 and Figure 14.

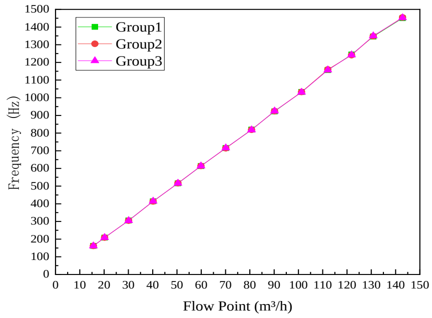

Figure 13: Effect diagram of single-phase gas frequency signal under repetitive measurement.

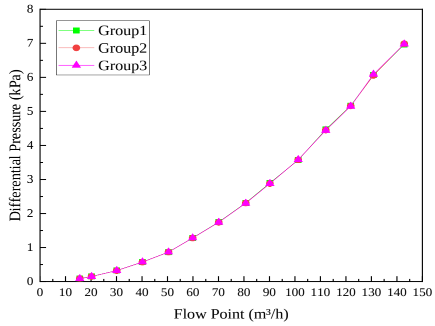

Figure 14: Effect diagram of single-phase gas differential pressure signal effect diagram under repetitive measurement.

The error analysis of the accuracy of the differential pressure signal and the frequency signal is carried out by the measurement device, as shown in Figure 15. The relative errors of the two signals are kept within ±1.50%.

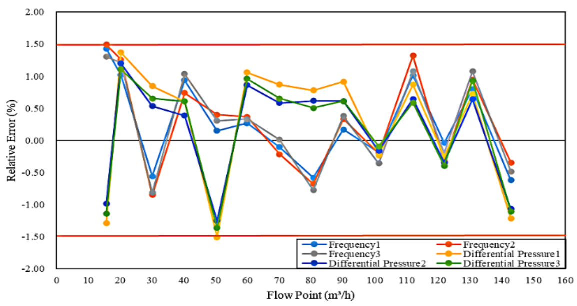

Figure 15: The relative error of the measurement of the two signals under different gas flowrate points.

5. Conclusion

In this paper, a new type of flow measurement device is proposed. The device scientifically combines the advantages of the averaging-velocity tube and the vortex flowmeter, which greatly improves the wide applicability, anti-interference and reliability of the device. The conclusions are as follows:

(1) In this paper, a new type of flow measurement device is designed based on the structural characteristics of the averaging-velocity tube and the vortex street. The device is equipped with a detection cylinder and a probe. The differential pressure signal is generated on both sides of the detection cylinder, and the probe vibrates to transmit the frequency signal.

(2) The device adopts DSP technology and replaces the traditional analog filter with a digital filter. The CPU of the device can adjust and process in real time according to the sensor signal. The frequency range of the filter is automatically tracked and selected according to the frequency of the signal, thereby greatly improving the flexibility, reliability and stability of signal processing. And further improving the anti-interference ability of the device.

(3) Through the analysis of the experimental test results of single-phase gas and single-phase water, the mathematical models for vortex frequency, differential pressure and volume flow rate are established respectively. Experimental results show that the absolute value of the relative error of single-phase water is within 1.00%, and the absolute value of the relative error of single-phase gas is within 1.50%. The device can achieve dual-signal measurement, and has good repeatability and stability, which will provide a certain theoretical basis for the measurement of saturated wet steam.

Acknowledgements

The authors are grateful for the support by the National Natural Science Foundation of China, China (62173122), Key Project of Natural Science Foundation of Hebei Province (F2021201031), Beijing-Tianjin-Hebei Collaborative Innovation Community Construction Project (20540301D) and Hebei Provincial Postgraduate Demonstration Course Project (KCJSX2021009).

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