A new method for processing ultrasonic gas flowmeter signal in wet gas

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Abstract
Gas velocity as an important characteristic parameter of wet gas has become a very active research issue in engineering field. Among many gas velocity measurement techniques, the ultrasonic flowmeter technique is more suitable for actual working conditions. However, the traditional signal processing methods of ultrasonic flowmeter are only proposed for single-phase gas. In wet gas, the ultrasonic signals fluctuate greatly, are easily distorted and even lost, so the single-phase ultrasonic signal processing methods are not applicable. Therefore, a new ultrasonic signal DBSCAN clustering synthetic peak method is proposed to solve the above problems. To verify the feasibility of this new proposed method, three real flow experiments are carried out on horizontal pipe at ambient temperature and pressure. Additionally, comparing the gas velocity results using ultrasonic signal double threshold method and ultrasonic empirical model method for single-phase gas and the new proposed method for wet gas, it is shown that the measurement results using new proposed method accord with the theoretical law and can accurately measure the gas velocity. Furthermore, the three real flow experimental results show that the repeatability of gas velocity in wet gas by the new proposed method is mostly <0.5%.

1 | INTRODUCTION

In ISO/TR 11583 technical report, the gas–liquid two-phase flow with gas volume fraction greater than 95% is defined as wet gas [1]. As a special gas-liquid two-phase flow, wet gas exists widely in various fields of industrial production. In recent years, the wet gas measurement has become a very active research issue in two-phase field. Gas velocity is one of the important characteristic parameters of wet gas, and its measurement techniques and methods are significant for the study of hydrodynamic characteristics and heat transfer characteristics of wet gas.

Compared with other gas velocity measurement techniques, the ultrasonic measurement technique has a wider measurement range and a strong universality, which is suitable for a variety of pipe diameters [2]. Recently, various ultrasonic flowmeters have been developed and different ultrasonic signal processing methods have been proposed, where, the time-of-flight (TOF) also called transit time ultrasonic flowmeter is widely used to obtain the gas velocity. It mainly includes three measurement methods: ultrasonic signal double threshold (UDT) method, cross-correlation method, empirical model (UEM) method. As a traditional ultrasonic signal processing technology, UDT method is widely used in gas ultrasonic flowmeter. In 2014, Li et al. [3] presented the UDT method to achieve accurate time measurement, which can effectively suppress noise in the ultrasonic received signal in two paths ultrasonic gas flow measurement. In 2017, Zhu et al. [4] studied the characteristics of the ultrasonic echo signal, and proposed a variable ratio threshold and zero-crossing detection based digital signal processing method for ultrasonic gas flow meter. Additionally, based on the analysis of the amplitude of the extreme points under different flow rates, and according to the threshold value and the zero-crossing method, the ultrasonic transit time was calculated. Then the gas velocity and the flow rate were obtained. In 2018, Fang et al. [5] proposed a similarity judgment-based double-threshold method to deal with the cycle-skip problem in ultrasonic gas flowmeter measurement. The method guaranteed that the obtained TOF
located on the same positive zero-crossing point in each measurement and successfully eliminated cycle-skip phenomenon under different working conditions. Furthermore, in recent several years, the cross-correlation method is also used to process the ultrasonic signal. In 2001, Brassier et al. [6] developed an initial signal process based on the cross-correlation method for gas flowmeters. This method provided low uncertainty for the parameters involved in the flow measurement process. In 2017, Khyam et al. [7] proposed a threshold-based phase-correlation technique which is able to provide a much narrower peak than cross-correlation without increasing the signal's physical bandwidth. In 2019, Suñol et al. [8] pointed out that the selection of an appropriate reference wave in cross-correlation method is presumably a key element in the precise measurement of TOF. And they put forward a novel approach to determine the reference signal. Within this strategy, the analytical solution of an acoustically forced underdamped oscillator model is used as a reference signal. Results demonstrate that the algorithm provides high-precision measurements within a wide dynamic range. With the rapid development and maturity of mathematical algorithms, more and more UEM methods are used to process the signal of gas ultrasonic flowmeter. In 2006, Angrisani et al. [9] presented a new digital signal-processing method for ultrasonic TOF estimation, which applies the discrete extended Kalman filter to the acquired ultrasonic signal in order to accurately estimate the shape factors of the echo envelope as well as locate its onset. 2007, Kupnik et al. [10] employed a time and phase domain based detection algorithm that determines the absolute transit times independently for the upstream and downstream channel. In 2015, Zhou et al. [11] developed a modified artificial bee colony algorithm to estimate the parameters of ultrasonic echoes based on nonlinear Gauss echo model. Experimental results showed that this method not only can accurately estimate various parameters of the ultrasonic echoes, but also can achieve the optimal solution in the global scope. In order to obtain accurate TOF in the presence of noise for an ultrasonic gas flowmeter, Hou et al. [12] presented a new genetic-ant colony optimization method based on the exponential model. However, when the noise frequency is close to that of the desired signals, local convergence of genetic-ant colony optimization method may appear, and measurement accuracy may be affected. Therefore, in 2016, Zheng et al. [13] proposed an improved energy genetic-ant colony optimization-3cycles method to solve this problem. The above ultrasonic signal processing methods are all proposed for single-phase ultrasonic gas flowmeter. The UDT method needs a stable threshold voltage, the cross-correlation method needs a stable reference signal and the received signal will not be distorted, and the UEM method requires the signal envelope to be stable with little change. However, in the wet gas two-phase flow, because the gas phase and the liquid phase exist at the same time, and under the high liquid volume fraction (LVF), the single upstream and downstream ultrasonic signals may be lost. In addition, the flow pattern of wet gas is complex, and there are many factors affecting the measurement process. So, the ultrasonic received signals attenuate seriously and fluctuate greatly, which are easily affected by noise. Therefore, the single-phase ultrasonic gas flowmeter signal processing methods are not applicable.

In the 1990s, researchers and research institutes carried out research on gas ultrasonic flowmeters for wet gas flow measurement. In 2000, Zanker et al. [14] conducted the tests at CEESI (USA) with natural gas/decane and natural gas/Texsolve, and at NEL (UK) with Nitrogen/Kerosene to simulate the wet gas two-phase flow. The test matrix tried to cover pressure ranging from 2.5–7.5 Mpa, gas superficial velocity \((v_{sg})\) from 2–20 m/s, and LVF from 0.1–5%. Ultrasonic wave propagation effects were observed on several meter diagnostic parameters, and the challenge was to find a simple correlation between pressure, \(v_{sg}\) and LVF. In 2006, CiDRA Corporation [15] presented a measurement method which combined a differential pressure-based gas flow meter with a SONAR-based flow meter to provide two independent measurements of the wet gas mixtures, each with distinct and repeatable over-report characteristics due to wetness. The performance of the combination was characterized at pressures of 1.38–6.9 Mpa, over flow velocities ranging from 20–80 ft/s, and for wetness ranging from 0–0.2 Lockhard–Martinelli numbers. The results showed that the combination can accurately measure gas flow rates within ±2% and liquid rates within ±10%. In 2012, FLEXIM [16], a German ultrasonic flowmeter manufacturer, used a clamp-on gas ultrasonic flowmeter to measure wet gas flow in horizontal pipe. The experimental pressure was 3–7.5 Mpa, and the LVF ranged from 0–5%. The experimental results showed that the effects of the wetness of \(v_{sg}\) and LVF. In 2014, Xing et al. [17] proposed an error correction model for ultrasonic gas flowmeter to explore the potential of an ultrasonic flowmeter for metering gas-liquid stratified and annular flows under different system pressures including 0.2–0.5 MPa and the gas and liquid superficial velocities \((v_{sg} \text{ and } v_{li})\) from 4–30 m/s and 0.01–0.7 m/s, respectively. A single-path ultrasonic flowmeter was investigated and the error of the apparent volumetric flowrate was considered as mainly resulting from the shrinkage of the gas flow path due to the presence of a liquid phase. In summary, it is feasible to measure the gas velocity of wet gas with ultrasonic gas flowmeter. Although some researchers have studied the ultrasonic measurement on wet gas, they focus on the test and results of existing products. Due to commercial secrets and other reasons, these studies only give some macroscopic laws and the specific signal processing principles and methods of these measurement schemes have not been published to the public and are unknown.

For these reasons, in this paper, based on the single-phase ultrasonic gas flowmeter, the ultrasonic signal DBSCAN clustering synthetic peak (UDCSP) method is proposed to process the complex signals in wet gas. Moreover, the advantages of this UDCSP method are further demonstrated by comparing with the traditional UDT method and UEM method in detail. Besides, the reliability of this proposed UDCSP method is verified by three real flow experiments.
2 | MEASUREMENT PRINCIPLE

2.1 The principle of TOF ultrasonic gas flowmeter

The TOF ultrasonic flowmeter has been widely used in oil and gas measurement due to many advantages such as simple principle, high reliability, and convenient installation [18]. The measurement principle of TOF ultrasonic gas flowmeter is illustrated in Figure 1.

Two transducers are installed in the different sides of the pipe. The gas velocity and sound speed in the pipe are \( v_g \) and \( c \). The diameter of the pipe is \( D \). The length of the acoustic path between the two ultrasonic transducers is \( L \). The acoustic path angle is \( \theta \). The TOF for the upstream and downstream are \( t_u \) and \( t_d \), as shown below:

\[
\begin{align*}
t_u &= \frac{L}{c} - \frac{v_g}{c} \cos \theta \\
t_d &= \frac{L}{c} + \frac{v_g}{c} \cos \theta
\end{align*}
\]

Using Equations (1) and (2), \( v_g \) can be derived as shown in Equation (3).

\[
v_g = \frac{L}{2 \omega_{\theta}} \left( \frac{1}{t_d} - \frac{1}{t_u} \right)
\]

For multi-path flowmeters, the calculation formula for the \( v_g \) is as follows:

\[
v_g = \sum_{i=1}^{m} \omega_i v_{g|i}
\]

Where, \( \omega_i \) is the weight coefficient of each acoustic path. \( v_{g|i} \) is the measured gas velocity for each acoustic path. \( m \) is the number of acoustic paths.

2.2 The ultrasonic signal double threshold method

As a traditional ultrasonic signal processing method, the UDT method is widely used in the gas velocity measurement of single-phase flow. Its measurement principle is shown in Figure 2. The first threshold voltage is used to determine whether the signal has arrived. And the black dot represents the feature point corresponding to the first threshold voltage. The second threshold voltage represents the obtained TOF corresponding to first negative zero-crossing (green dot) after the feature point.

2.3 The ultrasonic empirical model method

To obtain TOF accurately, much research based on ultrasonic pulse received signal models has been done which is called ultrasonic empirical model (UEM) method. There are two ultrasonic empirical models: Gaussian model and exponential model. Actual ultrasonic received signals are narrowband asymmetric and have low frequency, which is consistent with the exponential model [12]. So the exponential model is selected to identify the TOF of ultrasonic received signals. The exponential model (shown in Figure 3) of ultrasonic received signals is as follows [19–20]:

\[
A_g(k t_d) = A_0 \left( \frac{k t_d - \tau}{T} \right)^n e^{\frac{-k t_d}{T}} \quad (5)
\]

\[
A(k t_d) = A_0 \left( \frac{k t_d - \tau}{T} \right)^m e^{\frac{-k t_d}{T}} \quad (6)
\]
Where, $A_0$ is the signal amplitude, $T$ and $m$ are depending on the specific ultrasonic sensor, $\tau$ is the desired TOF, $t_s$ is the sampling period, $k$ is the sampling point serial number, $f_c$ is the ultrasonic transducer central frequency, $\vartheta$ is the initial phase, and $u(k^2-\tau)$ is the unit step signal. Additionally, $A_0$, $T$, $m$ and $\tau$ of the exponential model need to be determined. And the accuracy of ultrasonic gas velocity measurement mainly depends on the $\tau$.

2.4 The ultrasonic signal DBSCAN clustering synthetic peak method

The accuracy of gas velocity depends on the measurement of $t_u$ and $t_d$ which are difficult to determine because of the fluctuation and attenuation of ultrasonic signal in wet gas. And the single-phase ultrasonic flowmeter signal processing method is not applicable. So in this paper, the signal processing method of TOF ultrasonic flowmeter in wet gas is studied.

Due to the instability of flow field and the great influence of the liquid on the ultrasonic received signal during the wet gas measurement, even under the same working condition, the ultrasonic waveform change is quite sharp. Figure 4 presents three ultrasonic received signals under the same working condition with the $v_g$ of 10 m/s and LVF of 3%. It can be seen that there is a big difference including amplitude and envelope between ultrasonic original received signals. So, it is disadvantageous to analyse the law of all ultrasonic received signals. Therefore, in this paper, all the collected ultrasonic signals are first normalized. The comparison before and after the normalization processing of the ultrasonic received signal is as shown in Figure 5. As observed in Figure 5(a), the maximum peak value of ultrasonic received signal (Maxpeak) is about 0.18 V. And by dividing the each sampling point amplitude by Maxpeak, a normalized ultrasonic received signal with a maximum amplitude of 1 is obtained. Figure 5(b) presents the normalized ultrasonic received signal. It can be seen that the ultrasonic received signal has no distortion and the maximum amplitude is normalized to 1.

In the traditional gas ultrasonic flowmeter, the TOF is usually calculated according to a certain characteristic of ultrasonic received signal. As an important feature of ultrasonic received signal, the peak point is widely concerned by researchers [21]. In order to explore the law of ultrasonic received signal in each working condition, the peak points of upstream (downstream) ultrasonic received signal after normalization processing are extracted. Moreover, since the feature of the peak points with too small amplitude is not obvious and difficult to distinguish from the fluctuation of the noise signal, only the peak points (red asterisks) with amplitude >0.2 are extracted as shown in Figure 6.
In addition, under the condition of wet gas, there may be signal loss phenomenon. For example, only the downstream signal can be collected, but the upstream signal is not collected due to the influence of liquid phase. So, it is impossible to calculate the gas velocity accurately by single upstream and downstream ultrasonic received signal according to Equation (3). Therefore, in this paper, the traditional method of processing single upstream and downstream ultrasonic received signals is discarded, and a new UDCSP processing method of all ultrasonic received signals is adopted: Firstly, all upstream (downstream) ultrasonic received signals at each working condition are simultaneously processed. Then, an average upstream (downstream) ultrasonic TOF is calculated by all upstream (downstream) ultrasonic received signals. Finally, the average gas velocity under the working condition is obtained by using Equation (3). Hence, it is necessary to simultaneously extract the peak points of all the upstream (downstream) ultrasonic signals under each working condition. Figure 7 shows the peak point distribution of all upstream ultrasonic received signals in the \( v_g \) of 10 m/s and LVF of 3%. The following will take the ultrasonic received signals under this working condition as an example to introduce the UDCSP method in detail.

It can be seen from Figure 7 that the peak points fluctuate greatly under the same working condition. But each peak point presents a regular spatial density distribution in the form of data cluster, and fluctuates near its corresponding data cluster. So, the centre of each data cluster in Figure 7 is used as the basis for calculating the average TOF of the ultrasonic received signal.

In order to calculate the centre point of each data cluster in Figure 7, the clustering algorithm of Density-Based Spatial Clustering of Applications with Noise (DBSCAN) is introduced, which is a clustering algorithm based on the density characteristics of data samples [22–23]. The DBSCAN clustering algorithm can divide the data with enough high density into a cluster, also can find data cluster with any shape in the data sample database with noise. When using DBSCAN algorithm to cluster data samples, two parameters \( \varepsilon \) and \( \text{Minpts} \) need to be first defined. Where, \( \varepsilon \) is the algorithm’s clustering radius, and \( \text{Minpts} \) is the minimum number of data points in the neighborhood. Then, the algorithm randomly visits a certain data point which has not been visited in all data samples, also checks whether the number of other data points in the neighborhood with the radius of \( \varepsilon \) reaches \( \text{Minpts} \). If the number of other data points in the neighborhood of the data point does not reach \( \text{Minpts} \), the data point is considered as noise point or boundary point; Otherwise, a new cluster \( C \) is created and the data point is added to cluster \( C \), at the same time, all other data points in the neighbourhood of the data point are added to candidate set \( N \). After that, each data point in set \( N \) is checked iteratively. If there are other \( \text{Minpts} \) data points in the neighbourhood of a certain data point, all these data points are added to set \( N \). Next, all the data points in the set \( N \) are judged. If a certain data point is not a member of any cluster, the data point is added to the data cluster \( C \). Until all data in set \( N \) is checked and \( C \) is no longer extended, it is considered that data cluster \( C \) has been generated. Finally, the algorithm outputs the data cluster \( C \) and begins to randomly visit the next new unvisited data point. The above process is repeated to find the next data cluster.

In this paper, the values of \( \varepsilon \) and \( \text{Minpts} \) are set to 2 and 80 by analysing the peak point distribution. Also, the above mentioned DBSCAN clustering algorithm is used to cluster the peak points of ultrasonic received signal in Figure 7. Figure 8 illustrates the result of clustering the peak points. As shown in Figure 8, according to the density distribution characteristic of the peak points, all the peak points are divided into 14 different data clusters. Each data cluster represents the fluctuation range of one peak point in the ultrasonic received signals. But for each data cluster in Figure 8, it can be seen that there are still a few discrete data points. To eliminate the influence of these discrete points on the signal processing, 50 discrete points farthest from the centre of each data cluster are filtered out. And the remaining valid data points are utilized to calculate the centre point of each data cluster which is called synthetic peak point in this paper. Therefore, the corresponding synthetic peak point...
The synthetic peak point of each data cluster can be expressed as follows.

\[ X_{\text{syn_peak}} = \sum_{p=1}^{n} \frac{X_p}{n} \]  
\[ Y_{\text{syn_peak}} = \sum_{p=1}^{n} \frac{Y_p}{n} \]  

Where, \( X_{\text{syn_peak}} \) and \( Y_{\text{syn_peak}} \) are the horizontal and vertical coordinate values of the synthetic peak point. \( n \) is the number of remaining valid data points. \( X_p \) and \( Y_p \) are the horizontal and vertical coordinate values of the \( p \)-th valid data point. The synthetic peak point of each data cluster is given in Figure 9. Where, the green data points represent the valid data points after DBSCAN clustering and filtering for each data cluster. The red data points are the synthetic peak points calculated according to each valid data point.

From the Equation (3), it can be known that when calculating the gas velocity in the pipe under a certain working condition, \( t_u \) and \( t_d \) need to be obtained at the same time. So it is necessary to simultaneously use the UDCSP method to process all the upstream and downstream ultrasonic received signals under the working condition, and obtain a set of upstream and downstream synthetic peak points. Figure 10 shows that upstream and downstream synthetic peak points. It indicates that the upstream and downstream synthetic peak points have the obvious regularity in the rising part. Thus, the average upstream (downstream) ultrasonic TOF is calculated using the first five peak points in the rising part data points of the upstream (downstream) synthetic peak point. The \( t_u \) and \( t_d \) are calculated as shown below:

\[ t_u = \frac{\sum_{j=1}^{5} t_{u,j}}{5} \]  
\[ t_d = \frac{\sum_{j=1}^{5} t_{d,j}}{5} \]  

Where, \( t_{u,j} \) and \( t_{d,j} \) are the times corresponding to the \( j \)-th synthetic peak point in Figure 10. After, gas velocity can be calculated by substituting \( t_u \) and \( t_d \) into Equation (3).

Figure 11 presents the complete flow chart of the UDCSP method to process the ultrasonic received signals. Compared with the signal processing method of single-phase ultrasonic flowmeter, this UDCSP method clusters and processes all signals under the same working condition to obtain the synthetic peak points and TOF, which has better stability and repeatability.

3 | FLOWING EXPERIMENTS IN HORIZONTAL WET GAS TWO-PHASE FLOW

3.1 | Experimental design

The experiments are carried out on the dual-close recirculating loop wet gas test facility at Tianjin University, China. The facility is mainly composed of gas phase loop, liquid phase loop, horizontal test section and computer control system as shown in
In the gas phase loop, the medium is air. The standard meter is turbine flowmeter, whose measurement accuracy is 1.0% and adjustable range of gas flow rate is 10–400 m³/h. In the liquid phase loop, the medium is water. The standard meter is electromagnetic flowmeter, whose measurement accuracy is 0.35% and adjustable range of liquid flow rate is 0.05–8 m³/h. When the device is running, the air enters the gas phase loop using the piston fan, and the water enters the liquid phase loop using the water pump. The air and water are mixed in the gas-liquid mixer tube to form wet gas which then flows into the horizontal test section. The measured wet gas will be separated in the gas-liquid separator and circulated into the gas and liquid phase loop.

The gas velocity of wet gas measurement sensor section is as shown in Figure 13. The inner diameter of measurement pipe is 50 mm. The ultrasonic probe with a type of AT200 made by Airmar Company is selected, the center frequency is 200 KHz, and the diameter is 16 mm. Four ultrasonic probes are installed on both sides of the pipe in the form of ‘X’ mode. In wet gas two-phase flow, there will be liquid film around the pipe. And when the LVF is large, the liquid film thickness will be relatively thick [24]. In order to avoid the liquid film submerging ultrasonic probes and the ultrasonic probes being unable to receive the signals, the depth of four probes inserted into the pipe is set to 15 mm. Probe 1 and probe 3 form an acoustic path (called 1–3 path), probe 2 and probe 4 form an acoustic path (called 2–4 path). The angle between each acoustic path and the axial direction of the pipe is 45°, and 1–3 path is located in the middle of the pipe, 2–4 path is located above the middle of the pipe and at a distance of 9 mm from the middle. In addition, the self-developed hardware circuit is used to realize the excitation, amplification and filtering of ultrasonic signals. Then the received signal is transmitted to the NI6110 data acquisition board with the 4 MHz sampling frequency. Finally, the collected 2 minutes data is saved and processed by the computer.

Three real flow experiments are carried out under 32 working conditions at ambient temperature and pressure. The range of
$v_{sg}$ covered in the test is 5–20 m/s and LVF is 0.4–5%. In order to observe the actual flow pattern under various working conditions, the observation window is installed before the gas velocity measurement sensor section, as shown in Figure 14. And the flow patterns observed in this research are mostly stratified flow ($S$), wavy flow ($W$) and annular flow ($A$).

### 3.2 Experimental results and analysis

In this paper, three real flow experiments for every working condition are conducted, and the UDT method, UEM method and UDCSP method are compared. The comparison results are presented in Table 1. Where, UDT-single method is for single ultrasonic received signal, UDT-average method, UEM method and UDCSP method are for average of all ultrasonic received signals under a certain working condition.

It is observed that when the flow pattern is stratified flow, the gas-liquid interface is stable and there is no large fluctuation, and the gas velocity using the above methods can achieve the desired effect, where the gas velocity generally increases with the increase of LVF. At the same $v_{sg}$, because the gas flow rate into the pipe is certain, with the gradual increase of the LVF, the flow area of the liquid phase in the pipe becomes larger, and the flow area of the gas phase in the pipe becomes smaller. Consequently, the gas velocity of wet gas will increase. However, with the increase of LVF, the flow pattern appears wavy flow and the fluctuation of gas-liquid interface increases. The 1–3 path located in the middle of the pipe will be affected by the liquid phase at the bottom of the pipe, and the ultrasonic signals will be distorted or even lost, resulting in the wrong results using the traditional UDT-single method (in row 6, 7 and 8), where the gas velocity decreases with the increase of LVF. In addition, at larger gas velocity and LVF, the flow pattern becomes annular flow, both 1–3 and 2–4 paths will be affected by the liquid phase, which makes the gas velocity measured by UDT-single method not conform to the theoretical law (in row 12, 14, 15 and 16). Especially in row 16, the ultrasonic received signals of 1–3 path are seriously distorted due to the influence of liquid phase, resulting in a negative value of gas velocity. Moreover, The UDT-average method is used to first average all ultrasonic received signals under a certain working condition, and then perform a threshold judgment to obtain $v_{sg}$. It can be seen that this UDT-average method can improve the results of $v_{sg}$ on the basis of UDT-single method, but it still cannot eliminate the wrong results.

#### TABLE 1  Comparison between the results measured by UDT method, UEM method and UDCSP method

| Run | $v_{sg}$ [m/s] | LVF [%] | Flow pattern | $v_{g(1-3)}$ [m/s] | $v_{g(2-4)}$ [m/s] | $v_g$ [m/s] | $v_{g(1-3)}$ [m/s] | $v_{g(2-4)}$ [m/s] | $v_g$ [m/s] | $v_{g(1-3)}$ [m/s] | $v_{g(2-4)}$ [m/s] | $v_g$ [m/s] |
|-----|----------------|---------|--------------|-------------------|-------------------|------------|-------------------|-------------------|------------|-------------------|-------------------|------------|
| 1   | 5              | 0.4     | S            | 2.473             | 3.852             | 3.162      | 2.474             | 3.852             | 3.163      | 4.754             | 5.812             | 5.286      |
| 2   | 5              | 0.6     | S            | 2.515             | 3.973             | 3.245      | 2.515             | 3.973             | 3.244      | 4.845             | 6.000             | 5.431      |
| 3   | 5              | 0.8     | S            | 2.628             | 4.082             | 3.386      | 2.626             | 4.082             | 3.385      | 5.004             | 6.169             | 5.653      |
| 4   | 5              | 1.0     | S            | 2.741             | 4.111             | 3.426      | 2.738             | 4.109             | 3.424      | 5.199             | 6.221             | 5.705      |
| 5   | 5              | 2.0     | W            | 4.429             | 4.885             | 4.657      | 3.691             | 4.891             | 4.291      | 6.373             | 7.317             | 6.841      |
| 6   | 5              | 3.0     | W            | 7.411             | 4.336             | 5.874      | 11.762            | 5.623             | 8.693      | 7.117             | 8.263             | 7.690      |
| 7   | 5              | 4.0     | W            | 7.366             | 4.274             | 5.820      | 4.828             | 6.618             | 5.723      | 7.829             | –1.115            | 3.353      |
| 8   | 5              | 5.0     | W            | 2.841             | 4.891             | 3.866      | 5.040             | 6.711             | 5.876      | 8.056             | 10.109            | 9.098      |
| 9   | 10             | 0.4     | W            | 4.049             | 7.114             | 5.582      | 3.769             | 7.115             | 5.442      | 0.342             | 10.788            | 5.569      |
| 10  | 10             | 0.6     | W            | 5.605             | 7.382             | 6.493      | 6.529             | 7.379             | 6.954      | 0.993             | 11.188            | 6.098      |
| 11  | 10             | 0.8     | W            | 6.823             | 7.575             | 7.199      | 6.846             | 7.695             | 7.271      | 11.587            | 11.538            | 11.565     |
| 12  | 10             | 1.0     | W            | 6.917             | 3.892             | 5.405      | 7.090             | 1.392             | 4.241      | 11.896            | 11.889            | 11.891     |
| 13  | 10             | 2.0     | W            | 7.086             | 9.237             | 8.161      | 7.929             | 9.629             | 8.779      | 12.501            | 14.877            | 13.706     |
| 14  | 10             | 3.0     | A            | 6.156             | 10.008            | 8.082      | 1.409             | 10.328            | 5.868      | 13.045            | 15.992            | 14.533     |
| 15  | 10             | 4.0     | A            | 3.005             | 10.290            | 6.648      | 8.950             | 10.889            | 9.920      | 13.902            | 16.859            | 15.419     |
| 16  | 10             | 5.0     | A            | –0.293            | 9.624             | 4.666      | 9.242             | 11.285            | 10.264     | 14.311            | 17.437            | 15.839     |
Furthermore, the UEM method is utilized to simulate the ultrasonic received signal, and obtain $v_{sg}$ by least square algorithm. Because of the serious fluid fluctuation in the wet gas two-phase flow, the envelope of the ultrasonic received signals changes dramatically. As a result, the UEM method can't fully simulate the ultrasonic signals and produces the wrong $v_{sg}$ (in row 7, 9 and 10). But, the proposed UDCSP method can overcome the defects of above methods and ensure the accuracy of measurement. All the while with the increase of $v_{sg}$ and LVF, the gas velocity using UDCSP method increases gradually, which accords with the theoretical law. The above measurement results prove the correctness of the proposed UDCSP method.

Two typical working conditions are selected to analyse the error reasons caused by the UDT-single method (UDT-average method and UEM method have the same effect), also to explain the advantages of the UDCSP method as follows (The following will take the ultrasonic received signal under the 1–3 path downstream situation as an example to analyze the UDT-single and UDCSP method in detail).

At this flow condition of $v_{sg} = 5$ m/s and LVF = 0.6%, the flow pattern is stratified flow (in row 2), where the gas-liquid interface is stable and the coincidence of ultrasonic signals is good. It is observed from Figure 15(a) that the first threshold is set to 0.6, which satisfies all ultrasonic signals, and the TOF is stable. Therefore, this UDT-single method can accurately calculate the TOF for all ultrasonic signals under this working condition. The ultrasonic signals are processed by this UDCSP method as shown in Figure 15(b). This method can successfully find the synthetic peak points of all ultrasonic signals by DBSCAN clustering algorithm and also accurately calculate the TOF for all ultrasonic signals.

At this flow condition of $v_{sg} = 10$ m/s and LVF = 5%, the flow pattern is annular flow (in row 16), where the gas-liquid interface fluctuates greatly and the stability of ultrasonic signals is very poor. As shown in Figure 16(a), the fluctuation range of peak points of ultrasonic signals at the same position is larger and more dispersed. The first threshold cannot be found to satisfy all ultrasonic signals, so this UDT-single method calculates the wrong gas velocity and is no longer applicable to process the ultrasonic signals. Additionally, the UDT-single method calculates the gas velocity by single upstream and downstream ultrasonic received signal according to Equation (3). Therefore, the ultrasonic probe doesn’t receive the real signal, the noise will be mistaken for a real signal to be utilized and normalized. So some of the peak points in Figure 16(a) are disorganized. In the UDCSP method, because all peak points of ultrasonic signals under the same working condition are clustered to get a TOF without involving the TOF of each ultrasonic signal, so the noise signal is eliminated. As shown in Figure 16(b), the blue star is the peak point distribution after the noise signal is removed. Then this UDCSP method is used to cluster these processed peak points to obtain the synthetic peak points (red dots) and TOF. The UDCSP method overcomes the large fluctuation of ultrasonic signals and the irregular distribution of peak points, and successfully processes the signals and obtains the TOF. Compared with the UDT-single method, the feasibility and correctness of this proposed UDCSP method are verified again.

### 3.3 Gas velocity discussion using UDCSP method

The UDCSP method is utilized to process the all collected ultrasonic signals. The results are displayed in Figure 17.

In Figure 17(a–d), the calculation results of the average gas velocity in the three experiments with different LVF at the $v_{sg}$ of 5, 10, 15 and 20 m/s are given respectively. Detailed inspection of Figure 17 reveals that under each $v_{sg}$, the gas velocity generally increases with the increase of LVF. The trend of gas velocity variation in the three experiments is basically consistent with the theory.

However, in Figure 17(c,d), when the $v_{sg}$ is 15 m/s and the LVF is 5%, $v_{sg}$ is 20 m/s and the LVF is 3%, 4% and 5%, the calculation results of gas velocity decrease with the increase of the LVF. It may be caused by entrainment. In fact, when the $v_{sg}$ and the LVF are large, the phenomenon of liquid drop entrainment will become very obvious [25]. Since a part of the liquid in the pipe is entrained in the gas in the form of droplets, the...
flow area of the liquid in the pipe will be reduced and the flow area of the gas will be increased. Additionally, because the total gas flow rate into the pipe under a certain $v_{sg}$ is certain, the gas velocity of wet gas will be decreased.

Furthermore, the Bessel equation is used to calculate the repeatability RPV of the gas velocity in three experiments under each working condition, as shown in Equation (11).

$$\text{RPV} = \sqrt{\frac{1}{N-1} \sum_{k=1}^{N} \left( \frac{v_k - \bar{v}}{\bar{v}} \right)^2} \times 100\%$$  \hspace{1cm} (11)

$N$ is the number of the experiments where $N$ equals to 3. $v_k$ is the gas velocity calculated in the $k$-th experiment. $\bar{v}$ is the average gas velocity of $N$ experiments. Figure 18 presents the RPV of gas velocity calculation results in three experiments at each working condition.

The results show that the repeatability of gas velocity is less than 1% at different $v_{sg}$ and LVF. Under most working conditions, the repeatability is less than 0.5%. Consequently, it can be proved that the proposed UDCSP method in this paper has good repeatability and reliability.
FIGURE 18  the repeatability RPV of gas velocity calculation results in three experiments at each working condition

4  |  CONCLUSION

In view of the fluctuation and complexity of ultrasonic signal of wet gas, a new method called UDCSP method is proposed. It can overcome these defects that ultrasonic signals fluctuate greatly, are easily distorted and even lost, also ensure the accuracy of gas velocity of wet gas. The following conclusions are obtained:

1. A gas velocity measuring system for wet gas in horizontal flow by ultrasound is designed, which includes sensor section, self-developed hardware circuit section and data acquisition section.
2. For the complex characteristics of ultrasonic signals in wet gas, the detailed steps of processing the ultrasonic signal using this UDCSP method are given.
3. At ambient temperature and pressure, three real flow experiments in wet gas are carried out under 32 working conditions. Besides, the ultrasonic signals obtained from the experiments are processed by the UDT method, UEM method and proposed UDCSP method, and it is shown that affected by the large fluctuation and easy loss of signals, the results by the UDT method and UEM method are not correct at larger \( v_{sg} \) and LVF. While the proposed UDCSP method in this paper overcomes these above shortcomings, and can accurately measure the gas velocity of the horizontal wet gas two-phase flow. The UDCSP method lays a foundation for the study of the gas flow rate.
4. In the three experiments, the repeatability of the measurement results using UDCSP method for the gas velocity of wet gas at each working condition is \(<1\%\), mostly \(<0.5\%\). It verifies the correctness and reliability of the UDCSP method.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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