ISSN:3007-9640 DOI: https://doi.org/10.70114/acmsr.2025.3.1.P225

Simulation Study on the Influence of Contraction Expansion and Bending Pipeline on Gas Flow Measurement Accuracy

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Abstract. This paper conducts an analysis of three common types of typical disturbances encountered in industry, obtaining gas flow field distributions under different operating conditions through simulation studies. It further investigates their impact on the measurement errors of clamp-on ultrasonic flow meters. The study reveals that bend disturbances cause more significant distortion to the flow compared to expansion and contraction disturbances, necessitating longer downstream distances from the bend to achieve fully developed flow profiles. Additionally, at higher Reynolds numbers, the recovery rate of flow velocity profiles is slower, making it challenging to attain a fully developed flow state within short distances. Correction methods are required to reduce measurement errors. Correction factors at different distances downstream of the three disturbances are obtained through simulation, enabling higher precision measurements at relatively short distances downstream of disturbances. These findings hold significant implications for engineering practice.

Keywords: gas flow; disturbances; measurement error; correction factors; simulation

1. Introduction

Ultrasonic flow meters are instruments used for volumetric flow rate measurement, which can be categorized into inline and clamp-on types based on their usage methods [1]. Compared to inline ones, clamp-on ultrasonic flow meters feature easy assembly [2], and direct measurement without contact with the media, offering promising prospects for applications in online flow measurement and on-site instrument calibration [3]. However, the measurement accuracy of ultrasonic flow meters is significantly affected by the actual flow field [4]. Inline ultrasonic flow meters compensate for errors caused by uneven flow field distribution by utilizing multiple channels and rectifiers, thereby obtaining accurate measurement results. However, clamp-on ultrasonic flow meters do not possess this characteristic. When the installation position of the instrument fails to meet the requirements of a long straight pipe section, insufficiently developed flow inside the pipe can lead to significant measurement errors, posing considerable challenges to the instrument's application.

Correction of flow profiles can partially address this issue, and scholars have conducted research in this area. Veronika et al. [5] simulated the flow field in a single bent pipe, calculated correction factors for different setups, and validated the effectiveness of numerical simulations using experimental results. Wang et al. [6] investigated the influence of acoustic path configuration and flow meter orientation on correction factors under different disturbance conditions. Shi et al. [7] used a two-dimensional ray tracing method to study the effects of Reynolds number, profile velocity distribution, and temperature on correction factors. Hideki et al. [8] proposed theoretical calculations for laminar and turbulent profile correction factors and validated them through experiments. However, literature suggests that due to the superior propagation of sound in liquids compared to gases, the application and research of clamp-on ultrasonic flow meters are mainly focused on the liquid domain. The inherent errors in measurements of clamp-on ultrasonic flow meters caused by uneven gas flow fields have not been sufficiently studied. Nevertheless, this is crucial for its application in online gas flow measurement and flow meter calibration, highlighting the importance of further work in this area.

This study conducted simulation research on the most typical disturbance geometries in industry, obtaining gas flow field distributions under different operating conditions. Based on this, the study

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analysed the impact of uneven velocity profiles on measurement errors of clamp-on ultrasonic flow meters and calculated the corresponding correction factors. The research findings can provide reference and assistance for the application of clamp-on ultrasonic flow meters in gas flow measurement in real industrial settings.

2. Methodology

2.1 Simulation Method

This paper simulated three typical industrial disturbances: single-bend pipe, double-bend pipe, and externally mounted double-bend pipe, as illustrated in Fig 1. The upstream entrance length of the disturbance is 7 times the pipe diameter, ensuring the sufficient development of the flow pattern at the inlet [9]. Downstream of the disturbance, the pipe length is 100 times the pipe diameter. The mesh division is depicted in Fig 1, and the grid independence verification has been passed, the number of grids ranges from 2000000 to 3000000. The simulation was conducted using the Reynolds-Averaged Navier-Stokes (RANS) equations method, employing the RNG k-ε model. The inlet was set as a velocity inlet, while the outlet was set as a pressure outlet.

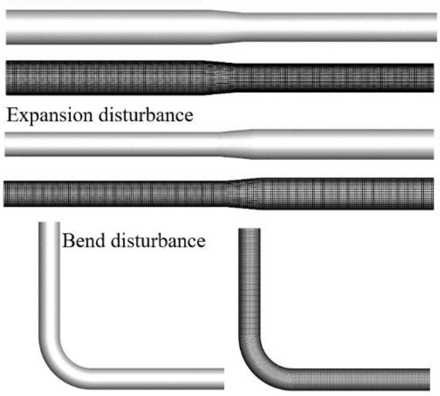

Fig. 1 Models and grids for three types of disturbances

2.2 Flow Calculation Method

Clamp-on gas ultrasonic flow meters utilize the time-of-flight method for measurement, as depicted in Fig 2. Due to the fluid flow through which the ultrasonic waves propagate, the propagation time of the ultrasonic signal in the downstream direction is shorter than in the upstream direction. By measuring the time difference in propagation, the average flow velocity along the propagation path is obtained. After flow profile correction, the area-averaged flow velocity and flow rate are obtained. Calculation methods can be referenced from [10,11]. In simulation, the time taken for signal propagation between transducers is obtained by integrating the velocity within each grid along the propagation path. This allows for the calculation of simulated values for velocity and flow rate.

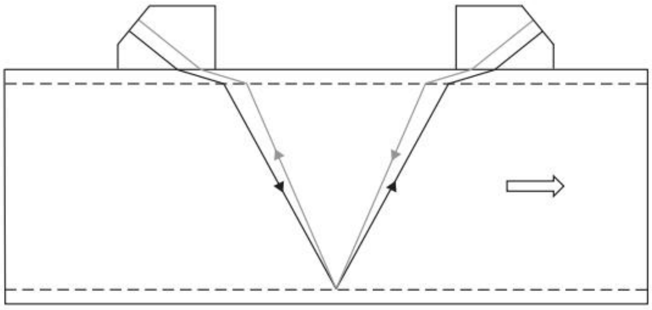

Fig. 2 The principle of flow measurement using external clamp ultrasonic flow meter difference method

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3. Results and Discussion

3.1 Influence of Disturbance Type on Flow Velocity Distribution

The variation of cross-sectional flow velocity distribution with downstream distance of contraction disturbance is shown in Fig 3. It can be observed that closer to the disturbance, the flow profile at the center is very flat. As we move closer to the downstream, the flow field develops more completely. Within a distance range of 50D downstream from this type of flow disturbance, the flow profile is essentially fully developed.

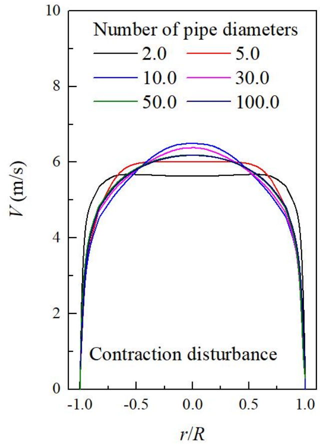

Fig. 3 The variation of cross-sectional flow velocity distribution of contraction disturbance

Fig. 4 displays the variation curve of cross-sectional flow velocity distribution with downstream distance of expansion disturbance. In contrast to the contraction trend, the jet exists at the center of the pipe for expansion. Closer to the disturbance, the flow profile at the center is very prominent. As the downstream distance increases, the jet gradually disappears, and the flow field develops more completely. At the same Reynolds number, expansion distorts the flow more significantly than contraction, meaning a longer downstream distance is needed for the flow profile to fully develop in the case of expansion.

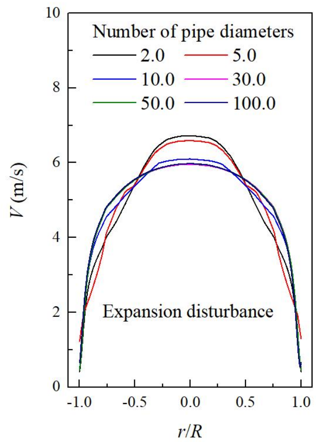

Fig. 4 The variation of cross-sectional flow velocity distribution of expansion disturbance

The variation of cross-sectional flow velocity distribution with downstream distance of a 90° single-bend pipe disturbance is depicted in Fig 5. It can be observed that compared to contraction and expansion disturbances, the velocity distribution within 10D downstream of the bend disturbance is more irregular. The flow velocity fluctuates significantly near the disturbance, showing a distribution with higher velocities at both ends and lower velocities in the middle. Even at a downstream distance of 20D, the velocity distribution still notably differs from the fully developed distribution. Beyond 30D, the flow field gradually returns to a stable state. The peak

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velocity positions gradually shift towards the center of the pipe. With the increase in the length of the straight pipe section, the degree of distortion in the velocity distribution caused by upstream flow obstacles diminishes gradually. The velocity distribution within the pipe gradually approaches a centrally symmetric distribution, resembling that of a long straight pipe.

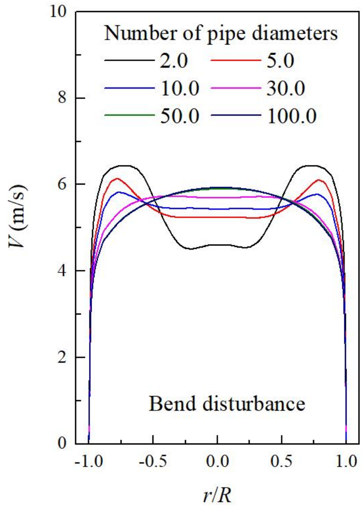

Fig. 5 The variation of cross-sectional flow velocity distribution of bend disturbance

3.2 Reference Correction Coefficient for Disturbance

Typically, when clamp-on ultrasonic flow meters are used for measurement or calibration, the accuracy specification of the equipment is required to be within ±2%, which is a comprehensive consideration of factors such as the selected disturbance type and distance. Therefore, by calculating correction factors through simulation, it is possible to achieve high-precision measurements at relatively short distances downstream of disturbances through reasonable quantitative flow compensation corrections. This is of significant engineering importance.

Fig. 6 illustrates the distribution of correction factors under three disturbance conditions, with inlet velocity ranging from 5 m/s to 20 m/s and installation distances from 3D to 100D. The results indicate that at higher Reynolds numbers and longer distances from the disturbances, the correction factor values are higher. This also suggests that at higher Reynolds numbers, the vortices and disturbances generated by pipe disturbances have a longer propagation time downstream, introducing greater non-uniformity to the flow field. At distances of 3-10D downstream of the disturbances, correction factors of 2%-6% are required for gradual contraction and expansion pipes, while a much higher correction factor of up to 8% is necessary downstream of the 90-degree bend, enabling measurement results to achieve high accuracy.

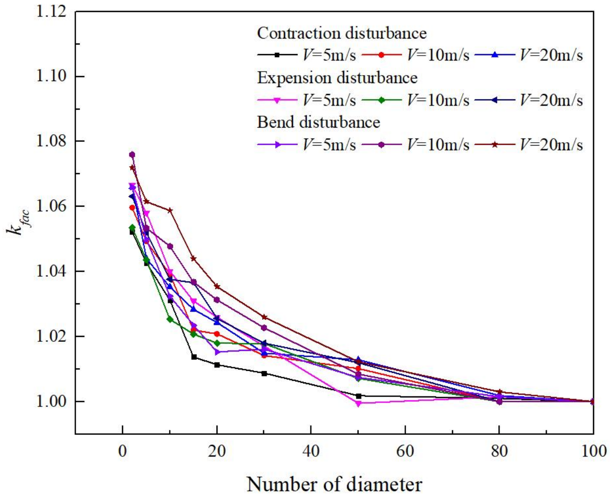

Fig. 6 The variation of cross-sectional flow velocity distribution of bend disturbance

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4. Summary

This paper analyses three common types of typical disturbances in industry, obtaining gas flow field distributions under different operating conditions, and examines their impact on the measurement errors of clamp-on ultrasonic flow meters. It quantitatively determines the correction factors at different distances downstream of different disturbances. The main conclusions are as follows.

(1) Bend disturbances cause greater distortion to the flow compared to expansion and contraction disturbances, requiring longer distances downstream of the bend to achieve fully developed flow profiles.

(2) At higher Reynolds numbers, the recovery of flow velocity profiles is slower, making it challenging to achieve a fully developed flow state within short distances. Correction methods are needed to reduce measurement errors.

(3) Correction factors at different distances downstream of the three disturbances are obtained through simulation, enabling higher precision measurements at relatively short distances downstream of disturbances. This has significant engineering implications.

Acknowledgements

This work is supported by scientific research funded project of Chongqing Market Supervision Bureau under Grand No. CQSJKJDW2024008.

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