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# 2D and 3D numerical simulation results of vortex flowmeter under nonideal installation conditions

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**Abstract**

An air test line of 50mm diameter was used in experiments covering two kinds of straight pipe length, and the numerical simulation results of vortex shedding frequency, which originated from the ANSYS FLUENT analysis results, were proved to be highly consistent with the experimental results. Based on this comparison, flow field simulation studies, including 13 pipe conditions, were carried out to establish the effect of upstream and downstream elbow fittings on the performance of the vortex flowmeter. The results indicated that the influences of the upstream straight pipe length were more obvious than the downstream straight pipe length. When there was an upstream elbow, the frequency value was greatly reduced, and the maximum error was -60.62%. The closer the elbow was to the vortex generator, the larger the decrease. The downstream elbows had a relatively small influence on the measurement results, and the maximum error was -13.23%. Considering the asymmetry of the 2D pipeline, the 3D simulations of part of the pipeline condition were further executed. The differences between 2D and 3D calculation results were analyzed, and the application value of different simulation results was explored.

## 1. Introduction

Since the development of the vortex flowmeter in the late 1960s, it has developed very rapidly and can be applied to liquid, gas and steam. It is a relatively advanced and ideal flow meter. However, the vortex flowmeter is still a developing flowmeter, and its theoretical basis and practical experience are relatively lacking. Therefore, it is still necessary to do a lot of basic research on the vortex flowmeter to avoid some unexpected problems in the actual use process[1].

The vortex flowmeter has certain requirements on the length of the straight pipe section and the roughness of the pipe wall during use. The calibration results and the stability of the flow rate depend on the length of the upstream and downstream straight pipe sections and the composition of the throttle components. And the vortex flowmeter can maintain the corresponding accuracy only if it meets the corresponding requirements[2]. The upstream elbow will cause an asymmetrical swirling flow in the pipeline, and the existence of the vortex will affect the pressure distribution near the wall of the pressure tap, which will affect the metering results of the flowmeter[3]. The University of Surrey in the United Kingdom and the British National Engineering Laboratory[2], the National Institute of Metrology of Japan[4], and Zheng Dandan of Tianjin University[5], etc., respectively, carried out experimental studies in the measurement performance of vortex flowmeters under different installation conditions. The actual flow experiments can obtain the specific measurement results under certain conditions, but the change and characteristics of the internal flow field of the pipeline cannot be observed.

Using the numerical simulation method to study the fluid flow field can observe the change of the flow field in real time, which has a strong guiding significance for studying the specific characteristics of the flow field. In recent years, many scholars have used computer simulation to conduct a lot of research on the characteristics of vortex flowmeters[6-9].

For vortex flowmeters, the length of the straight pipe section is insufficient or there is a bend in the upstream and downstream close distance, etc., which will obviously affect the measurement results, leading to a significant reduction in measurement accuracy and even affecting the accuracy of the trade handover. However, in the actual installation process, due to site restrictions or unreasonable pre-engineering design, the actual installation conditions often fail to meet the requirements. In this paper, numerical simulation was used to study the influence of non-standard installation conditions on the measurement results and internal flow field of vortex flowmeter after verifying the feasibility of the simulation method, and the related reasons were analyzed.

## 2. Measuring principle of vortex flowmeter

The vortex flowmeter uses the principle of fluid vibration to measure the flow. Under certain flow conditions, a part of the kinetic energy of the fluid is converted into vibration, and the vibration frequency has a certain proportional relationship with the flow velocity (fluid flow).

A non-streamlined vortex generator is placed in a direction perpendicular to the flow direction of the measured medium. When the fluid flows through the vortex generator, two rows of regular vortices are alternately separated and released on the rear sides of the body-facing surface. The vortex street generation process and flow measurement process are shown in Figure 1.

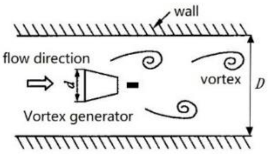


**Figure 1:** Schematic diagram of vortex generation process and flow measurement.

The average flow velocity *v* of the fluid in the pipeline and the vortex shedding frequency *f* satisfied Equation (1):

$$v = \frac{f \cdot m \cdot d}{S_t} \qquad (1)$$

In the Equation，

*v*- Flow rate of the measured fluid，m/s;

*f*- Vortex shedding frequency，Hz;

*m*- The ratio of the sum of the arched flow areas on both sides of the vortex body to the cross-section of the pipe;

*d*- The width of the intercepting surface of the vortex generator，m;

$S_t$- Strauhal number.

In a certain Reynolds number range, $S_t$ can be regarded as a constant, and the vortex flow sensor measures the fluid flow rate by detecting the vortex frequency *f*, and then obtains the flow value.

## 3. Simulation of vortex flowmeter flow field

### *3.1 Simulation model establishment and computational condition setting*

ANSYS ICEM was used to build geometric model of the corresponding pipeline and then divided the grid. The model was divided into three types: the upstream and downstream were straight pipe sections, the upstream had a single 90° elbow, and the downstream had a single 90° elbow. The dimensions of the vortex generator were shown in Fig. 2. The schematic diagram of the designed simulation pipeline was shown in Fig. 3. The diameter of the pipeline(D) was 50mm, while *n* was a variable which indicated the length of different pipelines. The monitoring parameter was the static pressure at 0.7 d (d: the width of the inlet surface of the vortex body) after the vortex generator.

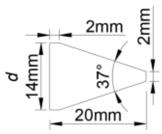


**Figure 2:** The size of vortex generator.

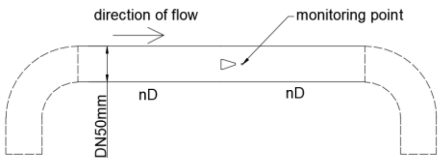


**Figure 3:** Design schematic diagram of the pipeline.

### *3.2 Comparison of experimental results with simulation results*

In order to confirm the feasibility of the research method, an air test line of 50mm diameter was used in experiments covering two kinds of straight pipe length. Experiments were carried out on the critical flow venturi nozzle method gas flow standard device (negative pressure method) of Xinjiang Metrology and Testing Institute. The device information was as follows: $U_{rel}$=0.25% (*k*=2), the flow range was (0.1-15000) $m^3/h$. The experimental equipment adopted the piezoelectric vortex flowmeter commonly used in industry, the diameter was DN50 mm, the size of the vortex generator was the same as that of the simulation, and the calibration accuracy of the vortex flowmeter was ±1.5%. Two experimental pipeline conditions were selected, which were upstream10D-downstream10D and upstream5D-downstream10D, respectively. The experimental conditions were basically the same as those defined by simulation.

**Table 1:** Relative error between 2D simulation data and experimental data.（%）

| Pipeline condition | 5m/s | 10m/s | 20m/s | 30m/s |
|---|---|---|---|---|
| upstream10D-downstream10D | -6.27 | -3.93 | -3.48 | 2.33 |
| upstream 5D-downstream10D | -8.78 | -5.49 | 4.69 | 2.89 |

Table 1 showed the error between the simulation data and the experimental data, it showed that the two were closed to each other and the maximum error was -8.78%, which indicates that the flow field simulation applied by FLUENT could truly reflect the frequency of vortex shedding under actual conditions. The simulation results were credible. Therefore, it was also feasible to use FLUENT numerical simulation to study the flow field characteristics of vortex flowmeters under different installation conditions.

*3.3 Simulation results analysis*

The inlet flow rates of the air medium were adjusted to 5m/s, 10m/s, 20m/s, and 30m/s, respectively. After a certain number of steps, the waveform appeared periodically, as shown in Fig. 4a. The frequency of vortex shedding and the corresponding signal strength (Fig. 4b) were obtained by applying Fourier transform (FFT) to the pressure curve.

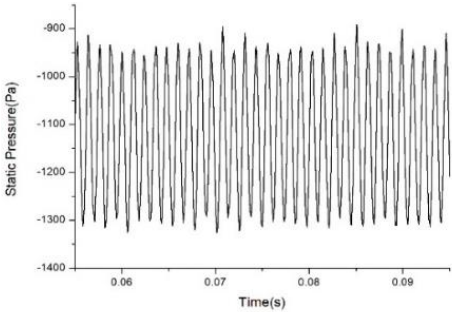


**Figure 4 a**. Waveform of static pressure at the monitoring point as a function of time period.

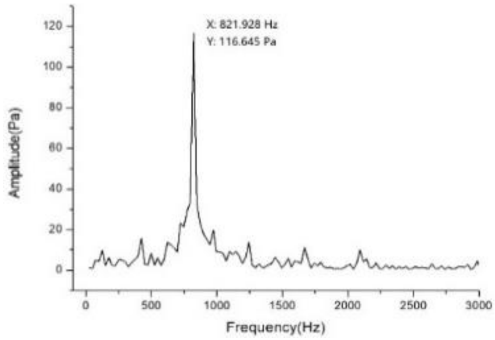


**Figure 4 b**. The frequency value and amplitude (ie, signal strength) obtained by the FFT processing of the waveform of the periodic variation.

For different inlet velocities, the distribution of vortex, velocity field and pressure field in the pipeline were similar. The difference was only the vortex shedding frequency *f* and amplitude. In Fig. 5, the calculation results were obtained when the length of the pipeline was upstream 10D -downstream 10D and the air velocity was 30m/s. It showed the vortex shedding in a certain period after the vortex generator. The vortices on both sides of the body alternately formed and fallen off, and the direction was opposite. The vortex intensity gradually decreased with the fluid flow.

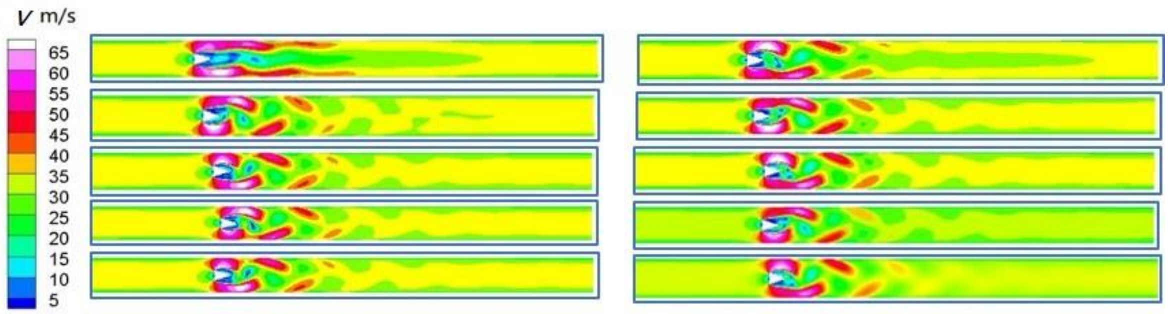


**Figure 5:** Vortex formation and shedding process during fluid flow

## 4. Analysis of simulation results under different pipeline conditions

Based on the above feasibility analysis, the flow field characteristics of the vortex flowmeter were analyzed at the upstream and downstream straight pipe section, the upstream elbows, the downstream elbows, respectively.

*4.1 Both upstream and downstream were straight pipelines*

The upstream and downstream were straight pipelines, including upstream10D-downstream10D, upstream5D-downstream10D, upstream5D-downstream3D, upstream3D-downstream1D, upstream1D-downstream1D, these five situations. The specific calculation results were shown in Fig. 6. It can be seen from the calculation results that as the length of the straight pipe section was shortened, the frequency value decreased, and the decrease of the upstream length of the straight pipe section had a more obvious effect on the results.

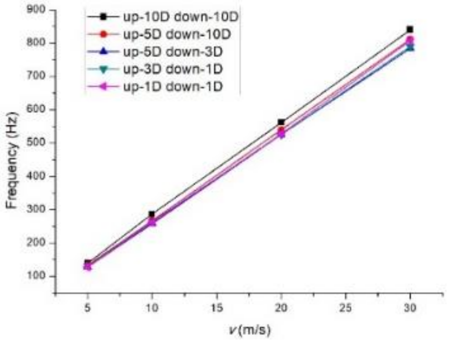


**Figure 6:** Calculation results corresponding to straight pipe sections of different lengths.

*4.2 There was a single 90° elbow upstream.*

The effect of upstream distance was measured by changing the straight pipe length (between the upstream fitting and the flowmeter) from 1D to 40D, and all the length of the downstream straight pipe section was 5D. The data of the upstream10D-downstream 10D was used as a reference. The calculation results under various pipeline conditions were shown in Fig. 7.

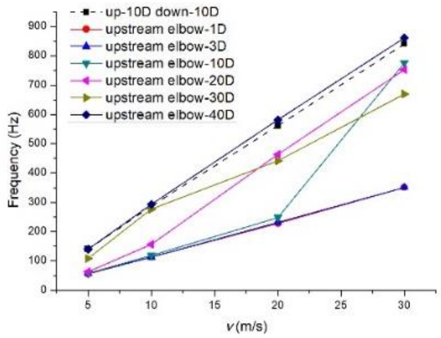


**Figure 7:** Calculation results corresponding to the front straight pipe length of different lengths of upstream elbow.

It could be seen that the shorter the length of the straight pipe section when there was an upstream elbow, and the closer the elbow was to the vortex generating body, the smaller the frequency value was, while the smaller the flow value in the pipe was. As the length of the straight pipe section increased, the frequency value gradually increased. If the upstream length of the straight pipe section was increased to 40D, the calculation result was close to the result when the straight pipe section was enough. It means that in the actual use, if the front end has a 90° elbow, the length of the front straight pipe section must not be lower than 40D. The frequency errors under each pipeline conditions were shown in Table 2.

**Table 2**: Relative error of simulation results with an upstream elbow （%）

| **Pipeline condition** | **5 m/s** | **10 m/s** | **20 m/s** | **30 m/s** |
|---|---|---|---|---|
| upstream1Delbow | -59.98 | -60.36 | -59.37 | -58.22 |
| upstream3Delbow | -58.10 | -60.62 | -58.69 | -58.27 |
| upstream10Delbow | -58.61 | -58.42 | -55.81 | -7.69 |
| upstream20Delbow | -54.06 | -45.27 | -17.40 | -10.38 |
| upstream30Delbow | -22.19 | -3.61 | -21.43 | -20.33 |
| upstream40Delbow | 0.26 | 2.15 | 3.46 | 2.51 |

The flow field characteristics of upstream-1D-elbow while the velocity of 30m/s were taken as an example to analyse the relevant flow field characteristics. It could be seen from the pressure cloud diagram (Fig. 8a) that, due to the presence of the elbow, the pressure distribution of the fluid on both sides of the pipe wall was uneven, the outside pressure increased, and the inner pressure decreased, while the inner side even formed a cavity when the flow velocity increases. The velocity vector diagram (Fig. 8b) showed the overall flow of the fluid in the pipe, where the pressure was low and the flow velocity was fast, the velocity vector density was high.

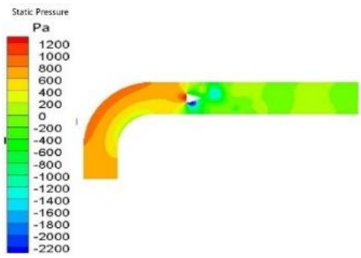


**Figure 8 a:** Pressure cloud diagram.

**Figure 8 b:** Velocity vector diagram.

The velocity cloud diagram (Fig. 9) fully reflected the influence of uneven pressure on both sides of the pipe wall: the outer side of the pipe wall had a higher pressure, the vortex fallen off faster, and the inner side was slower due to the lower pressure, resulting in a slower vortex shedding. The frequency of alternating vortex shedding on both sides of the body was reduced.

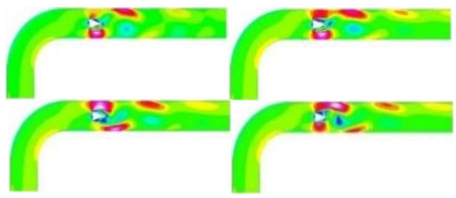

**Figure 9:** Velocity cloud diagram with elbow upstream.

*4.3 There was a single 90° elbow downstream.*

The downstream had a 90° elbow, including upstream10D-downstream5D elbow, upstream10D-downstream1D elbow, upstream1D-downstream5D elbow, upstream1D-downstream1D elbow, these four situations. The calculation results were shown in Figure 9. The frequency error was shown in Table 3.

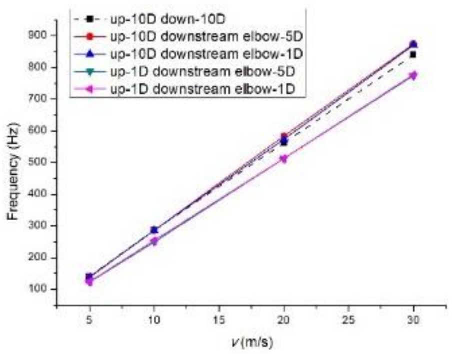


**Figure 9:** Calculation results corresponding to the straight pipe length of different lengths of downstream elbow.

It could be seen from the calculation results that when the upstream straight pipe length was 10D, the downstream elbow had less influence on the calculation results, and the maximum error was only 4.01%; but when the upstream straight pipe length was only 1D, the influence of downstream elbow was more significant, and the error was expanded to -13.23%. Therefore, if there was downstream elbow in the actual use, the length of the downstream straight pipe should not be shorter than 5D, to ensure the measurement accuracy to a certain extent.

**Table 3:** Relative error of simulation results with a downstream elbow（%）

| Pipeline condition | 5 m/s | 10 m/s | 20 m/s | 30 m/s |
|---|---|---|---|---|
| Upstream10D-downstream5Delbow | -0.76 | -0.48 | 3.88 | 4.01 |
| Upstream10D-downstream1Delbow | -1.44 | -0.55 | 2.05 | 3.68 |
| Upstream1D-downstream5Delbow | -12.05 | -13.23 | -8.82 | -7.85 |
| Upstream1D-downstream1Delbow | -11.44 | -11.65 | -8.74 | -7.53 |

As can be seen from the velocity cloud diagram (Fig. 10), In contrast to the upstream elbow, when there was a downstream elbow, the vortex on the inside of the pipe fallen off faster, and the outside was relatively slower. The frequency of pressure change slowed down, lead to the calculation result was also lower, which was consistent with the actual situation.

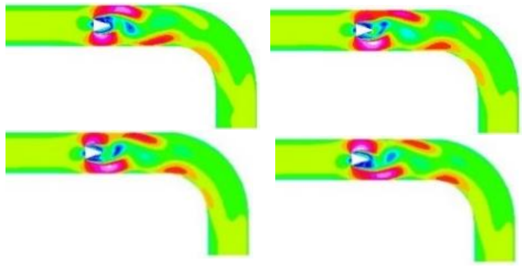

**Figure 10:** Velocity cloud diagram with elbow downstream.

## 5. Simulation results of 3D model.

Considering the asymmetry of the 2D pipeline, the 3D simulations of part of pipeline conditions were further executed. The 3D model of vortex flowmeter was shown in Fig. 11a. The geometric model was divided into different regions, which had different kind of mesh generation as shown in Fig. 11b.

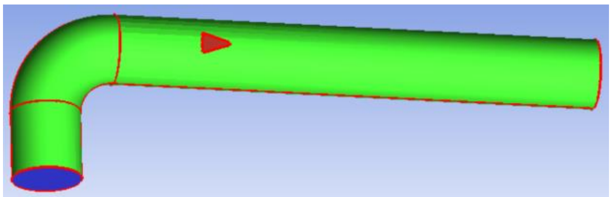

**Figure 11a:** The 3D model of vortex flowmeter.

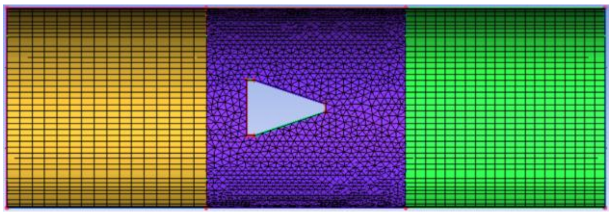

**Figure 11b**: The mesh generation of vortex flowmeter.

Table 4 showed the error between the 3D simulated data and the experimental data, and the results were compared with those obtained in 2D. It showed that the 3D simulation data were closer to the experimental data than 2D. This was because 3D models were more realistic.

**Table 4:** Relative error between simulation data and experimental data（%）

| Pipeline condition | 5 m/s | 10 m/s | 20 m/s | 30 m/s |
|---|---|---|---|---|
| upstream10D-downstream10D (2D) | -6.27 | -3.93 | -3.48 | 2.33 |
| upstream10D-downstream10D (3D) | -3.88 | -2.34 | -2.34 | 4.86 |
| upstream 5D-downstream10D (2D) | -8.78 | -5.49 | 4.69 | 2.89 |
| upstream 5D-downstream10D (3D) | -4.72 | -3.71 | 4.78 | 3.12 |

The results of different simulation methods under different pipeline conditions were shown in Table 5.

**Table 5:** Comparative results between 2D and 3D simulation data (Hz)

| Pipeline condition | 5 m/s | | 10 m/s | | 20 m/s | | 30 m/s | |
|---|---|---|---|---|---|---|---|---|
| | 2D | 3D | 2D | 3D | 2D | 3D | 2D | 3D |
| Upstream10D-downstream10D | 139.86 | 143.44 | 287.03 | 291.79 | 561.64 | 568.24 | 840.03 | 860.76 |
| Upstream5D-downstream10D | 134.66 | 140.65 | 266.88 | 271.90 | 539.98 | 540.43 | 811.64 | 813.45 |
| Upstream10Delbow-downstream5D | 57.89 | 62.41 | 119.36 | 120.86 | 248.18 | 250.12 | 775.45 | 404.77 |
| Upstream40Delbow-downstream5D | 140.22 | 141.39 | 293.21 | 295.43 | 581.05 | 588.92 | 861.12 | 863.79 |
| Upstream1D-downstream5Delbow | 123.01 | 118.41 | 249.06 | 237.98 | 512.09 | 482.91 | 774.12 | 734.67 |

## 6. Conclusion

To sum up, the feasibility of numerical simulation method was verified by experiments in this paper, and the influence of different pipeline conditions on the output of frequency value was studied. The specific conclusions were as follows:

1. When the upstream and downstream straight pipe lengths were insufficient, the shorter the straight pipe length was, the smaller the output frequency value was, and the corresponding calculated flow rate would be smaller. The reduction of the upstream straight pipe length had a more obvious impact on the results;

2. When there was a single upstream 90 ° elbow, the frequency value dropped dramatically. The closer the elbow was to the vortex body, the greater the reduction. When the length of the upstream straight pipe section was 40D, the calculation result was close to that when the upstream and downstream straight pipe sections were enough.

3. When the upstream straight pipe length was 10D, which met the installation requirements, the downstream 90 ° elbow had little effect on the calculation results. However, when the upstream straight pipe length was only 1D, the influence of downstream elbow was more significant, and the maximum error expanded to -13.23%.

4. The 3D simulation data was much closer to the experimental data than 2D, this was owing to 3D models were more realistic. The velocity distribution in the 3D pipeline was closer to the real situation.

For more pipeline conditions, including non-fully open gate valves upstream of the pipeline or elbows in different planes, the measurement results of vortex flowmeter and changes in internal flow field are the next research content.

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