Performance and application of an evaluation method for flow conditioner based on CFD

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Abstract. As evaluation of the performance of flow conditioner mostly depends on the specific pipeline system, which cannot be timely feedback to improve the structure design, an evaluation method for flow conditioner based on computational fluid dynamics (CFD) is promoted. First, the evaluation coordinates for flow conditioner is established and the coordinate values of each sampling point are solved. Then, the judgment basis of whether the velocity distribution of pipe cross-section is fully developed is derived, and then come to the evaluation index of flow conditioner rectifier performance. Finally, with CFD simulation technology, the verified experiments of grid format flow conditioner are performed. The results showed that, the proposed evaluation method is qualified to evaluate the grid format flow conditioner’s performance quickly and effectively. Besides, it is helpful to analyze the function of flow conditioner’s performance on Reynolds numbers. What’s more, when \(5.84 \times 10^6 \leq Re \leq 5.84 \times 10^8\), the required minimum length of straight pipe for irregular downstream field of the grid format conditioner achieving fully developed is only 0.5-0.6 times by those without conditioner. It is of great significance to accelerate the flow conditioner designed and to promote fluid energy monitoring.

1. Introduction
Flow regulator is an important device to accelerate the stability of irregular flow field and eliminate the influence of abnormal flow on fluid, such as vortex. It is widely used in the fields of fluid energy measurement and monitoring, flow monitoring system, flow sensor, etc [1]. Common flow regulators include tube bundle type, grid format, orifice plate, etc [2]. As the shape structure and installation mode of the regulator directly affects its working performance, the regulator designed for specific occasions frequently results in irregularity structure and performance of flow regulator in engineering application. In addition, unreasonable shape structure and irregular installation mode will even cause the downstream flow field of the regulator to be disordered and the rectification effect cannot be achieved [3]. Therefore, how to evaluate the rectification effect quickly and effectively is an important guarantee to improve the design efficiency and ensure the working performance of the regulator. For the moment, the performance evaluation of flow regulator basically needs to install the regulator into the pipeline and realize it indirectly according to the performance of its downstream flowmeter. This method relies on the specific pipeline system and flowmeter, which is cumbersome and costly. It can neither timely feedback and improve the regulator structure in the design stage, nor provide reference information for reasonable selection of flow sensor installation location [4-6]. For the past few years, CFD (Computational Fluid Dynamics) has been widely used in the field of flow monitoring. However, the research focuses on the flow field adaptability analysis of flowmeter under different temperature, pressure and flow conditions, and under the influence of elbow, valve and other disturbing parts [7-9].
At the same time, CFD technology is used to study the influence of transducer, reflector and other flowmeter structure on flow field [10-11], but there are few studies have been conducted to evaluate the performance of flow regulators by CFD alone [12-14]. In this paper, a performance evaluation method of flow regulator based on CFD simulation technology is proposed. The performance of flow regulator can be evaluated by CFD in the design stage, and the regulator design can be optimized timely according to the simulation structure, and the guidance information for the installation position of flow sensor can be provided.

2. Evaluation method of flow regulator
The purpose of the flow regulator rectification is to obtain the fully developed flow field consistent with that in the straight pipe under the same conditions, so the full development of the downstream flow field of the regulator directly reflects the performance of the regulator. Figure 1 is the flow chart of flow regulator evaluation method. Firstly, the watershed model is established by CAD (Computer Aided Design) and meshed by ICEM (Integrated Computer Engineering and Manufacturing) software.

Then, numerical simulation of straight pipe, double twist bend with regulator and double twist bend without regulator with that the boundary conditions of different experimental groups is carried out. Upon, the relative error of sample point velocity extracted from simulation results is calculated to judge whether the cross-section flow field is sufficient. Finally, the evaluation index of flow regulator is obtained.

![Flow chart of regulator evaluation method](image)

**Figure 1.** Flow chart of regulator evaluation method.
2.1. Establishment of sampling point coordinates

Figure 2 shows the coordinate system of flow regulator evaluation method, in which the surface O-XY is the lower end of regulator and the O point is section center. A plane follow-up polar coordinate system is established in section $\alpha_i$ of surface O-XY (distance $z_i (z_i > 0)$). $N_{o}(\alpha_i)$ circles with $\phi_j = d(j, \alpha_i)$ are selected from section $\alpha_i$, where $0 < j \leq N_{o}(\alpha_i)$, $0 \leq d(j, \alpha_i) < D_{pipe}$, $d(j, \alpha_i) \neq d(j+1, \alpha_i)$ and $D_{pipe}$ is pipe diameters. Sampling points $N_{p}(\phi_j, \alpha_i)$ are distributed on circle with $\phi_j = d(j, \alpha_i)$, then the coordinates of sampling point $P(k, \phi_j, \alpha_i)$ in the plane follow-up polar coordinate system is $\left( \frac{1}{2}\phi_j, \theta_k \right)$. Among them, $0 < k \leq N_p(\phi_j, \alpha_i)$, $\theta_k = \frac{2k\pi}{N_p(\phi_j, \alpha_i)}$. The coordinates $(x, y, z)$ of the sampling point $P(k, \phi_j, \alpha_i)$ in the coordinate system O-XYZ are:

$$\begin{cases} 
    x = \frac{1}{2}\phi_j \cos \theta_k \\
    y = \frac{1}{2}\phi_j \sin \theta_k \\
    z = z_i
\end{cases} \quad (1)$$

The total number of sampling points in the section $\alpha_i$ is $\sum_{j=1}^{N_{o}(\alpha_i)} N_{p}(\phi_j, \alpha_i)$.

2.2. Judgment of the full development of the cross-sectional velocity field

Whether the flow field downstream of the flow regulator is fully developed is reflected by the regularity of velocity distribution in the flow field. By comparing the flow field downstream of the regulator with the flow field in a pure straight pipe at the same pressure and temperature, the full development of the flow field downstream of the regulator can be quickly and effectively judged.
If the flow velocity of the sampling point \( P(k, \phi_j, \alpha_i) \) is \( v(k, \phi_j, \alpha_i) \) and the flow velocity of the pure straight pipeline under the same working condition is \( v_0(k, \phi_j, \alpha_i) \), the relative error of the flow velocity of the sampling point \( P(k, \phi_j, \alpha_i) \) is:

\[
\varepsilon(k, \phi_j, \alpha_i) = \frac{v(k, \phi_j, \alpha_i) - v_0(k, \phi_j, \alpha_i)}{v_0(k, \phi_j, \alpha_i)}
\]  

(2)

Based on the relative error in the CFD simulation process, if the relative error of the flow velocity of all sampling points in section \( \alpha_i \) satisfies \( \varepsilon(k, \phi_j, \alpha_i) \leq 0.05 \), it can be considered that the flow field at section \( \alpha_i \) has reached full development.

2.3. Evaluation indicators

To reflect the rectification effect of the flow regulator, it is necessary to solve the pipeline length required for the full development of the downstream flow field of the regulator. For sections \( \alpha_i \) and \( \alpha_{i+1} \), if it satisfies:

\[
\begin{align*}
&\varepsilon(k, \phi_j, \alpha_i) > 0.05 \\
&\varepsilon(k, \phi_j, \alpha_{i+1}) \leq 0.05 \\
&|z_i - z_{i+1}| \leq \Delta z
\end{align*}
\]

(3)

Then section \( \alpha_{i+1} \) is the section where the flow field reaches full development fastest, and \( z_{i+1} \) is the minimum straight pipe length required for the flow field downstream of the regulator to achieve full development, that is, the evaluation index of the rectification effect of the flow regulator. The smaller \( z_{i+1} \) indicates the rectification effect of the regulator. The better, the faster the flow field develops fully; if \( z_{i+1} \) is the same, the \( \varepsilon(k, \phi_j, \alpha_{i+1}) \) is smaller, the regulator performance is better. In Formula (3), \( \Delta z \) is the accuracy of the cross-section distance, and \( \Delta z = 0.1mm \) is taken in this paper.

3. Simulation scheme

3.1. Simulation system structure

Figure 3 shows the structure of the simulation system. The double-twisted elbow pipe is 5\( D_{\text{pipe}} \) apart from the flow regulator. At the same time, the upstream of the double-twisted elbow pipe is set with 10\( D_{\text{pipe}} \) straight pipe, and the downstream of the flow regulator is set with 100\( D_{\text{pipe}} \) straight pipe.

The experiment uses of AMCA flow regulator (grid type), the regulator belongs to the blade structure, the blade distribution crisscrossed and equal spacing, the segmentation area is presented as a small grid, and the more the number of blades, the smaller the segmentation area, the better the performance of rectification. Reasonable application of this type of regulator in flow measurement can effectively improve or even eliminate flow distortion, thus improving measurement accuracy [15]. Figure 4 shows the structural diagram of flow regulator. The pipe diameter is \( D_{\text{pipe}} = 50mm \), the regulator length is \( l_{\text{AMCA}} = 0.45D_{\text{pipe}} = 22.5mm \), and the grid width is \( 0.075D_{\text{pipe}} = 3.75mm \).

In the simulation scheme design, ICEM software was used to divide the established pipeline and flow regulator model into grids. The grid type was set as a hexahedral structured grid, and the number of meshes was 2 million. This kind of grid can deal with boundary conditions conveniently and accurately, and the calculation accuracy is high. Many efficient implicit algorithms and multi-grid methods can be used, and the computational efficiency is also high. In addition, the pipeline boundary
layer and flow regulator are also encrypted in the process of mesh division to further improve the accuracy of the calculation results.

**Figure 3.** Simulation system structure diagram.

**Figure 4.** Structure and shape of flow regulator.

### 3.2. Simulation conditions setting

The operating pressure of the simulation experiment is $P=0.6\text{MPa}$, the temperature $T=300\text{K}$, the fluid medium is water, the density of water is $\rho_w=996.799\text{kg/m}^3$, the dynamic viscosity is $\mu_{\text{in}}=8.54\times10^{-4}\text{kg/m}\cdot\text{s}$ . In this experiment, the inlet velocity of pipeline is set as $v_{\text{inlet}}=[0.1,0.5,1.3,5,8,10]\text{m/s}$, and the corresponding Reynolds numbers are respectively $Re=[5.84\times10^6,2.92\times10^7,5.84\times10^7,1.75\times10^8,2.92\times10^8,4.67\times10^8,5.84\times10^8]$.

Since the Reynolds number is always greater than 2400 during the experiment and the fluid flow is turbulent, the standard $k-\varepsilon$ model is adopted for the calculation model [16]. The standard $k-\varepsilon$ model is the most widely used model in industry at present. It has the advantages of short calculation time, high stability and calculation accuracy, and is very suitable for turbulent flow under high Reynolds number. Each Reynolds number corresponds to a set of experiments, and the experiments are carried out on pure straight pipes, double-twisted elbow pipes with regulators, and double-twisted elbow pipes without regulators under the same conditions.

### 4. Analysis of the simulation result

Table 1 shows the simulation experiment results, in which the x-coordinate is Reynolds number, and the y-coordinate is the minimum length of straight pipe $Z$. After calculation, the performance comparison analysis diagram of the AMCA flow regulator is obtained, as shown in Figure 5.

As you can see from Figure 5, whether or not a flow regulator is installed on the pipeline, the minimum straight pipe length $Z$ of the two experiments are shown to be correct, with the increase of
Reynolds number, which is specifically manifested as when \( Re < 2 \times 10^8 \), the growth rate of \( Z \) is relatively large; when \( Re > 2 \times 10^8 \), the growth rate of \( Z \) is relatively slow. The only difference is that the fluctuation range of the growth rate of \( Z \) is more dramatic under the condition of the flow regulator. This is because when the pipe diameter is constant, the greater the flow velocity is, the more unstable the flow field is, and the longer the straight pipe length is needed to reach the fully developed turbulent flow state. And the flow instability under the condition of low Reynolds number effect is more apparent, and once the Reynolds number reaches or exceeds a critical value, the flow field distribution will not change significantly with the increase of the flow velocity. At this time, it can be considered that the flow velocity is not sensitive to the influence of the flow field in the pipeline. Therefore, the growth rate of \( Z \) overall shows a changing trend that increases first, then slowly decreases and finally tends to be constant with the increase of Reynolds number.

After further combing, we also found the following that: 1. At any Reynolds number in the experimental range, the minimum straight pipe length \( Z_{AMCA} \) with AMCA regulator is much smaller than \( Z' \) without regulator, which indicates the AMCA regulator greatly accelerates the full flow field downstream of the regulator. The development shows that the evaluation method in this article can effectively reflect the rectification effect of the regulator in the experiment; 2. The minimum straight pipe length \( Z_{AMCA} \) with AMCA regulator is basically 0.5–0.6 times of the minimum straight pipe length \( Z' \) without AMCA in Reynolds number \( 5.84 \times 10^6 \leq Re \leq 5.84 \times 10^8 \).

![Figure 5. AMCA performance comparison analysis chart.](image)

| Experiment number | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
|-------------------|-----|-----|-----|-----|-----|-----|-----|
| Inlet flowrate (m/s) | 0.1 | 0.5 | 1   | 3   | 5   | 8   | 10  |
| Reynolds number    | 5.84×10^6 | 2.92×10^7 | 5.84×10^7 | 1.75×10^8 | 2.92×10^8 | 4.67×10^8 | 5.84×10^8 |
| Minimum straight pipe length with AMCA \( Z_{AMCA} \)(mm) | 720 | 890 | 940 | 1085 | 1380 | 1520 | 1590 |
| Minimum straight pipe length without AMCA \( Z' \)(mm) | 1260 | 1870 | 2075 | 2310 | 2350 | 2450 | 2490 |
| \( Z_{AMCA}/Z' \) | 0.5714 | 0.4759 | 0.4530 | 0.4697 | 0.5872 | 0.6204 | 0.6385 |

5. Conclusions
This thesis proposes an evaluation method of flow regulator based on CFD and studies the application of this method on AMCA flow regulators, and obtains the following conclusions:

1. When the diameter of the pipe is constant, the larger the flow velocity (or \( Re \)) is, the more unstable the flow field is, and the longer the minimum length of the straight pipe section required for the full development of turbulent flow state will be. However, with the increase of the flow velocity
(or $Re$), the increase rate of the minimum length of straight pipe is firstly increased, then decreased and finally leveled off. Specifically, when $Re<2\times10^6$, the growth rate of $Z$ is relatively large; when $Re>2\times10^6$, the growth rate of $Z$ is relatively slow.  

2. The evaluation method not only effectively reflects the rectification effect of the AMCA regulator, but also verifies that when the AMCA regulator is installed at the 5Dpipe downstream of the double-twisted band, the length of the straight pipe required for the full development of the irregular flow field downstream of the regulator is greatly shortened. For example, when $5.84\times10^5 \leq Re \leq 5.84\times10^6$, the minimum straight pipe length $Z$ required for the full development of the irregular flow field downstream of the AMCA regulator is only 0.5~0.6 times of that without the regulator.

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