Performance Evaluation and Analysis of a New Flow Conditioner Based on CFD

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Abstract. Accurate flow measurement is one of the key aspects of energy saving, while flow conditioner is an important part for accurate flow measurement. Flow conditioner is an effective device in accelerating distortion flow fully developed. Its performance affects the accuracy of a flow meter downstream. In this study, the performance of Etoile flow conditioner downstream a vortex generator is discussed, finding that removing the center area vanes and adding vanes near the inner wall could modify the conditioner’s performance. Then an octagonal star shaped improvement method is proposed according to the performance analysis of Etoile flow conditioner. With CFD (computational fluid dynamics) technology, the scope of the octagonal star shaped vanes added is demonstrated. Finally, a modified flow conditioner configuration based on the octagonal star shaped improvement method proposed and its performance are delineated. From the results obtained, it is effectual modifying Etoile flow conditioner with the octagonal star shaped improvement method.

1. Introduction
Accurate flow measurement is one of the key aspects of energy saving, while flowmeter is the main equipment for flow measurement. Thus, the accuracy of flowmeter has a direct relationship with energy saving. However, many disturbances like value, contracted pipe and elbow are commonly exist in practical pipeline systems, which will undoubtedly spark off flow distortion [1, 2]. One typical method using to eliminate the flow distortion is applying sufficient straight pipe upstream a flowmeter. According to A.G.A Report No. 9, 50D_{pipe} length of straight pipeline is required when asymmetric flow exists, while a 200D_{pipe} length of straight pipeline is needed to eliminate the effect of turbulence [3]. Applying such a long straight pipe is hardly practical while considering space and cost. Another common way to eliminate the flow distortion is to install a flow conditioner upstream a flowmeter [4, 5]. It does not need such a long straight pipe as A.G.A Report No. 9 reported while a flow conditioner exists [6]. Etoile flow conditioner has been used for years and many researchers have studied how to modify its performance. McHugh A., Kinghorn F. C., and Dyet W. D. investigated the performance of Etoile flow conditioner downstream two 90° elbows in perpendicular planes, finding Etoile was helpful to remove swirls but the flow downstream was still asymmetric [7]. Then the group researched on how the length of Etoile affected the flow conditioner’s performance, drawing a conclusion that at least 1D_{pipe} long it is, can Etoile totally remove swirls. Besides, 5D_{pipe} ~14D_{pipe} length is need between Etoile and orifice plate if you want to hold the effect on orifice coefficient less than 5% [8]. Laws E.
M. and Ouazzane A. K. cut off the central portion of Etoile flow conditioner changing it into an ‘open’ version, and found out that the ‘open’ version could be used upstream of another flow conditioner to produce improved overall performance [9]. Then Ouazzane A. K. and Barigou M. found a vaned-plate flow conditioner, consist of 6 vanes attached to a 70% porosity plate i.e. the ‘open’ version described in [9], could improve the performance of the meter [10]. Laribi B., Youcefi A. and Matene E. investigated the performance of Etoile flow conditioner downstream a valve maintained at 100% and 50% open with numerical simulation, finding when the valve is 50% open, Etoile flow conditioner would achieve the best performance at $2D_{\text{pipe}}$ length [11, 12]. How would the flow conditioner perform if more vanes are added in Etoile is still worth investigation.

CFD (short for Computational Fluid Dynamics) technique has been widely used to investigate a flow conditioner. Gonzalez-Trejo J et al evaluated the effect of the thickness and length of the flow conditioner on the overall performance of the submerged nozzle with CFD technique, finding out flow conditioner should be as thin as possible [13]. Liu R et al used CFD technique to explore how a VAV flow conditioner regulate the velocity profile upstream of the VAV airflow sensor and increase the VAV airflow measurement accuracy, pointing out that it is a common way to evaluate the performance of a flow conditioner by examining the velocity profile downstream of it [14]. Thus, in this paper, CFD technique is applied to investigate the flow conditioner’s performance.

The outline of this paper is as follows. In Section 2, two kinds of velocity errors are calculated to evaluate the flow conditioner’s performance. Firstly, how to sample velocities with CFD technique is described. Then, the formulas to calculate the velocity errors are performed, using the sampling velocities. Thirdly, the physical meanings of the velocity errors are defined. In Section 3, analysis of Etoile flow conditioner performance is performed. Firstly, the pipeline configuration and boundary conditions of simulation are introduced. Then, the performance of Etoile conditioner at Plane: $Z=5D_p$ is discussed to find out the factors that may influence the performance of Etoile conditioner. In Section 4, in response to those factors discussed in Section 3, a new conditioner structure modified from Etoile is proposed, and how the new conditioner performs is analyzed. In Section 5, conclusions are given and the future work direction is elaborated.

2. Flow Conditioner Evaluation Method

The fully developed velocity profile is the aim of installing a flow conditioner, thus it is reasonable to evaluate a conditioner’s efficiency via the velocity distribution. In this paper, focusing on the velocity profile, the error of velocity between fully developed flow and the flow downstream flow conditioner is calculated to analyze the conditioner’s performance, where the fully developed flow is obtained from straight pipe without any disturbances. As it is impractical to integrate all velocities distributed downstream a flow conditioner, the discrete sampling method is adopted to calculate the velocity errors. With CFD technique, two kinds of velocity errors are calculated through sampling velocities from different locations. The sampling points’ distribution is shown in Figure 1. The Cartesian coordinate system O-XYZ is established on the downstream surface of flow conditioner, where the Z axis is the pipeline centerline. Forty-nine sample points are scattered in each cross-section Plane: $Z=Z_{dx}$ and they are numbered counterclockwise. The velocity errors are defined as below.
Figure 1. Coordinate system and sample points distribution at Plane: \( Z = Z_k \)

A. \( \overline{\varepsilon}_{\Sigma, z_k, r_i} \): Average velocity deviation of Pitch circle \( r_i \) at Plane: \( Z = Z_k \). \( \overline{\varepsilon}_{\Sigma, z_k, r_i} \) is used to analyze velocity distribution at a certain pipeline cross-section. According to Figure 1, \( \overline{\varepsilon}_{\Sigma, z_k, r_i} \) is calculated as

\[
\overline{\varepsilon}_{\Sigma, z_k, r_i} = |\bar{v}_i - \bar{v'}_i|, \tag{1}
\]

\[
\overline{\varepsilon}_{\Sigma, z_k, r_i} = \frac{1}{12} \sum_{j=1}^{12} |v_i - v'_i|, \tag{2}
\]

\[
\overline{\varepsilon}_{\Sigma, z_k, r_i} = \frac{1}{12} \sum_{j=1}^{24} |v_i - v'_i|, \tag{3}
\]

\[
\overline{\varepsilon}_{\Sigma, z_k, r_i} = \frac{1}{12} \sum_{j=25}^{36} |v_i - v'_i|, \tag{4}
\]

\[
\overline{\varepsilon}_{\Sigma, z_k, r_i} = \frac{1}{12} \sum_{j=37}^{48} |v_i - v'_i|, \tag{5}
\]

Where \( \bar{v}_i \) is velocity with a flow conditioner; \( \bar{v'}_i \) is velocity fully developed.

\( \overline{\varepsilon}_{\Sigma, z_k, r_i} \) displays how the velocity errors distribute at Plane: \( Z = Z_k \). It could be helpful to find out the week points of a flow conditioner. If \( \overline{\varepsilon}_{\Sigma, z_k, r_i} \) goes large, it means the structure at the corresponding positions may need improvement.

B. \( \overline{\varepsilon}_{\Sigma, z_k} \): the accumulated velocity deviation at Plane: \( Z = Z_k \). \( \overline{\varepsilon}_{\Sigma, z_k} \) is used to analyze how velocity errors distribute as \( Z_k \) changes. It is calculated as

\[
\overline{\varepsilon}_{\Sigma, z_k} = \frac{1}{49} \sum_{i=0}^{48} |v_i - v'_i| . \tag{6}
\]

\( \overline{\varepsilon}_{\Sigma, z_k} \) displays the distribution of the velocity errors downstream a flow conditioner. It could be helpful to find out the optimal location for installing a flow meter, and could be used to compare the performance of different conditioner structures as \( Z_k \) increases.

\( \overline{\varepsilon}_{\Sigma, z_k, r_i} \) and \( \overline{\varepsilon}_{\Sigma, z_k} \) are simply calculated through sampling velocities, and they can give an expression of the distribution of velocity errors. Thus, it would be reasonable to investigate the performance of a conditioner by using \( \overline{\varepsilon}_{\Sigma, z_k, r_i} \) and \( \overline{\varepsilon}_{\Sigma, z_k} \). Besides, as CFD technique is applied, none
particular flowmeter is need, while a particular flowmeter is necessary without CFD. Therefore, $\Sigma_{kizr}$ and $\Sigma_{kz}$ are convenient and suitable for different kinds of flow conditioners.

3. Analysis of Etoile Flow Conditioner performance based on CFD

With CFD (computational fluid dynamics) technology, simulation of Etoile flow conditioner downstream a vortex generator [15] is performed. Figure 2 demonstrates the pipeline configuration of simulation, where Etoile is installed $5D_{pipe}$ downstream the vortex generator, and $5D_{pipe}$ long straight pipe is set upstream the vortex generator while $100D_{pipe}$ long straight pipe is applied downstream Etoile. The diameter of pipeline is 50mm, i.e. $D_{pipe}=50$mm. The flow medium is incompressible water, whose density is $996.7$kg/m$^3$ and dynamic viscosity is $8.54\times10^{-4}$Pa.s. The operating pressure is $0.6$MPa and the flow temperature is $300$K. The inlet velocity is $1$m/s or $10$m/s. Thus, the Reynolds number is $5.84\times10^4$ or $5.84\times10^5$, and the k-ε model is adopted.

![Figure 2. The pipeline configuration of simulation.](image)

Figure 3 shows the distribution of $\bar{\varepsilon}_{\Sigma_{kizr}}$ at Plane: $Z=5D_p$. Using $\bar{\varepsilon}_{\Sigma_{kizr}}(E)$ stands for the $\bar{\varepsilon}_{\Sigma_{kizr}}$ of Etoile conditioner, and $\bar{\varepsilon}_{\Sigma_{kizr}}(X)$ stands for the $\bar{\varepsilon}_{\Sigma_{kizr}}$ of no conditioner, it is demonstrated in both Fig3(a) and Fig3(b) that $\bar{\varepsilon}_{\Sigma_{kizr}}(E) > \bar{\varepsilon}_{\Sigma_{kizr}}(X)$ while $|r/D_p| \leq 0.1$. This phenomenon might be caused by the vanes in region $|r/D_p| \leq 0.1$. That is to say, removing the vanes in region $|r/D_p| \leq 0.1$ might be helpful to get better velocity distribution. Similar idea has been put into practice in [16]. Besides, while $|r/D_p| > 0.3$, $\bar{\varepsilon}_{\Sigma_{kizr}}(E)$ gradually increases. It might be in region $|r/D_p| > 0.3$, the vanes distribution is too sparse. Therefore, adding vanes in region $|r/D_p| > 0.3$ is likely helpful in stopping $\bar{\varepsilon}_{\Sigma_{kizr}}(E)$ increasing again while $|r/D_p| > 0.3$.
Figure 3. Average velocity deviation of Pitch circle $r_i$ at Plane: $Z=5D_p$; (a) $Re=5.84 \times 10^4$. (b) $Re=5.84 \times 10^5$.

4. New Configuration and its performance’s analysis

Based on the analysis of Etoile conditioner performance above, an octagonal star shaped improvement structure shown in Figure 4 is proposed. The vanes in region $|r_i/D_p| \leq 0.1$ are removed, and eight vanes forming an octagonal star are added in $|r_i/D_p| > 0.3$. The distance between adding vanes and the center of pipe cross-section is defined as $h_{vane}$. Changing the value of $h_{vane}$ we can get vary flow conditioners. In this paper, four cases with different values of $h_{vane}$ (CASE I: $h_{vane}=0.3D_{pipe}$; CASE II: $h_{vane}=0.325D_{pipe}$; CASE III: $h_{vane}=0.354D_{pipe}$; CASE IV: $h_{vane}=0.4D_{pipe}$) are studied to investigate how $h_{vane}$ affects the flow conditioner’s performance.

Figure 4. Modified flow conditioner configuration.

With the same pipeline configuration of simulation shown in Figure 2 but changing the flow conditioner, simulations of CASE I–IV are performed in the same boundary conditions with analyzing the Etoile conditioner.

Figure 5 demonstrates the distribution of average velocity deviation of Pitch circle $r_i$ at Plane: $Z=5D_p$. Use $\bar{e}_{\Sigma_{z_i} r_i}(E)$, $\bar{e}_{\Sigma_{z_i} r_i}(I)$, $\bar{e}_{\Sigma_{z_i} r_i}(II)$, $\bar{e}_{\Sigma_{z_i} r_i}(III)$, $\bar{e}_{\Sigma_{z_i} r_i}(IV)$ and $\bar{e}_{\Sigma_{z_i} r_i}(X)$ standing for the $\bar{e}_{\Sigma_{z_i} r_i}$ of Etoile conditioner, CASE I, CASE II, CASE III, CASE IV and no conditioner respectively. While $Re=5.84 \times 10^4$, we can almost get $\bar{e}_{\Sigma_{z_i} r_i}(E) > \bar{e}_{\Sigma_{z_i} r_i}(III) > \bar{e}_{\Sigma_{z_i} r_i}(IV) > \bar{e}_{\Sigma_{z_i} r_i}(II) > \bar{e}_{\Sigma_{z_i} r_i}(I)$ from Fig.5 (a). In CASE I: $h_{vane}=0.3D_{pipe}$, $\bar{e}_{\Sigma_{z_i} r_i}(I)$ goes relatively stable, and has much better performance.
than $E_{x \cdot z_k \cdot r}$ in region $|r_i/D_p| < 0.1$; While $Re=5.84 \times 10^5$, we have $E_{x \cdot z_k \cdot r}^{(IV)} > E_{x \cdot z_k \cdot r}^{(III)} > E_{x \cdot z_k \cdot r}^{(I)}$ from Fig. 5(b) when $|r_i/D_p| \leq 0.1$. CASE I: $h_{vane}=0.3D_{pipe}$ still does the best in all six cases simulated. Besides, no matter $Re=5.84 \times 10^4$ or $Re=5.84 \times 10^5$, in region $|r_i/D_p| > 0.3$, there is no sign of rising in $E_{x \cdot z_k \cdot r}^{(I)}$, $E_{x \cdot z_k \cdot r}^{(II)}$, $E_{x \cdot z_k \cdot r}^{(II)}$ or $E_{x \cdot z_k \cdot r}^{(IV)}$. It indicates that removing the vanes in region $|r_i/D_p| \leq 0.1$ and adding an octagonal star vanes, whose $h_{vane}=0.3D_{pipe}$, do have a significant improvement to the flow conditioner.

Figure 5. The distribution of average velocity deviation of Pitch circle $r_i$ at Plane: $Z=5D_p$. (a) $Re = 5.84 \times 10^4$. (b) $Re = 5.84 \times 10^5$.

Figure 6 displays the accumulated velocity deviation of different pipe cross-section. Use $E_{x \cdot z_k \cdot r}^{(E)}$, $E_{x \cdot z_k \cdot r}^{(I)}$, $E_{x \cdot z_k \cdot r}^{(II)}$, $E_{x \cdot z_k \cdot r}^{(III)}$ and $E_{x \cdot z_k \cdot r}^{(K)}$ standing for the $E_{x \cdot z_k}$ of Etoile conditioner, CASE I, CASE II, CASE III, CASE IV and no conditioner respectively. $E_{x \cdot z_k}^{(K)}$ is dramatically larger than those with a conditioner like $E_{x \cdot z_k}^{(E)}$, $E_{x \cdot z_k}^{(I)}$, $E_{x \cdot z_k}^{(II)}$, $E_{x \cdot z_k}^{(III)}$ or $E_{x \cdot z_k}^{(IV)}$. No matter $Re=5.84 \times 10^4$ or $Re=5.84 \times 10^5$, we have $E_{x \cdot z_k}^{(I)} < E_{x \cdot z_k}^{(E)}$ within $0 \leq z_k \leq 20D_p$, and $E_{x \cdot z_k}^{(I)} \approx E_{x \cdot z_k}^{(E)}$ while
It means CASE I: $h_{vane} = 0.3D_{pipe}$ has a better performance than Etoile conditioner within $0 \leq z_k \leq 20D_p$, and could be the optimal configuration in all cases simulated.

![Figure 6](image1.png)
![Figure 6](image2.png)

**Figure 6.** The accumulated velocity deviation of different pipe cross-section; (a) $Re = 5.84 \times 10^4$, (b) $Re = 5.84 \times 10^5$.

5. Conclusion
Accurate flow measurement is one of the key aspects of energy saving, while flow conditioner is an important part for accurate flow measurement. Simulations with CFD technology are performed to investigate the performance of Etoile flow conditioner downstream a vortex generator, finding that the Etoile conditioner is helpful to modify the abnormal flow field but still can be improved. For one thing, the vanes in region $r_i/D_p \leq 0.1$ are too much to obstruct the fluid. For another, the vanes in region $r_i/D_p > 0.3$ are too sparse, which makes the abnormal fluid near the region can not be effectively modified. In response to these week points above, a new flow conditioner structure modified from Etoile conditioner is proposed. The new flow conditioner, that has removed the vanes in region $r_i/D_p \leq 0.1$ and added an octagonal star shaped vanes in region $r_i/D_p > 0.3$, could have a better performance than Etoile. Specially, when the distance between vanes added and center of pipe cross-section is $0.3D_{pipe}$, modified flow conditioner gets the optimal configuration. When $Re = 5.84 \times 10^4$ or $Re = 5.84 \times 10^5$, the optimal configuration has a better performance than Etoile conditioner within $0 \leq z_k \leq 20D_p$. 

$z_k > 20D_p$. It means CASE I: $h_{vane} = 0.3D_{pipe}$ has a better performance than Etoile conditioner within $0 \leq z_k \leq 20D_p$, and could be the optimal configuration in all cases simulated.
At the present stage, the proposed structure is a topological flow conditioner in theory. Through theoretical analysis in this paper, the proposed structure is of quite a better performance than Etoile, and it has been recommended to the Guangzhou Basic Controls company to consider for practical application.

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