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Theoretical and numerical study of hydraulic characteristics of orifice energy dissipator

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Abstract: Different factors affecting the efficiency of the orifice energy dissipator were investigated based on a series of theoretical analyses and numerical simulations. The main factors investigated by dimension analysis were identified, including the Reynolds number (*Re*), the ratio of the orifice diameter to the inner diameter of the pipe (d/D), and the ratio of distances between orifices to the inner diameter of the pipe (L/D). Then, numerical simulations were conducted with a k-ε two-equation turbulence model. The calculation results show the following: Hydraulic characteristics change dramatically as flow passes through the orifice, with abruptly increasing velocity and turbulent energy, and decreasing pressure. The turbulent energy appears to be low in the middle and high near the pipe wall. For the energy dissipation setup with only one orifice, when *Re* is smaller than 10^5, the orifice energy dissipation coefficient *K* increases rapidly with the increase of *Re*. When *Re* is larger than 10^5, *K* gradually stabilizes. As d/D increases, *K* and the length of the recirculation region L_1 show similar variation patterns, which inversely vary with d/D. The function curves can be approximated as straight lines. For the energy dissipation model with two orifices, because of different incoming flows at different orifices, the energy dissipation coefficient of the second orifice (K_2) is smaller than that of the first. If L/D is less than 5, the *K* value of the L/D model, depending on the variation of K_2, increases with the spacing between two orifices L , and an orifice cannot fulfill its energy dissipation function. If L/D is greater than 5, K_2 tends to be steady; thus, the *K* value of the L/D model gradually stabilizes. Then, the flow fully develops, and *L* has almost no impact on the value of *K*.

Key words: *orifice energy dissipator; theoretical analysis; numerical simulation; k-ε two-equation turbulent model; hydraulic characteristics*

1 Introduction

The orifice energy dissipator is a new energy dissipation method that dissipates the energy within outlet works. The general mechanism of the orifice energy dissipator can be summarized as follows: by using a sharp-edged orifice to generate sudden enlargements in tunnel flow, a large amount of energy can be dissipated over a small distance.

The advantages of the orifice energy dissipator (Li 1999) are as follows: optimization of the project layout; reduction of difficulty in energy dissipation in mountainous areas, which always have a limited spatial area; and resolution of the complex technical problems related to

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high heads and velocities that cannot be solved by conventional energy dissipation methods. Although it is known that many factors may influence the efficiency of the orifice energy dissipator, the mechanisms of orifice energy dissipators are not yet fully understood.

Until now, most research on orifice energy dissipators has been conducted through experiments (Cai et al 1999; Chen et al. 2006; Wei et al. 2006; Yang et al. 2004), which can only provide parameters for total flow. Practical data are also far from sufficient. However, numerical simulation can provide information on the total distribution of each parameter. Moreover, the numerical results are not affected by the scale effect of physical model tests. With advances in computer science and technology, the computational models have become highly efficient and can be used with greater convenience and higher precision. In this study, dimension analysis was conducted to identify the main factors that affect the orifice energy dissipator. Then, numerical simulations were conducted with a k - ε two-equation turbulence model for energy dissipation to investigate the main factors.

2 Theoretical analysis

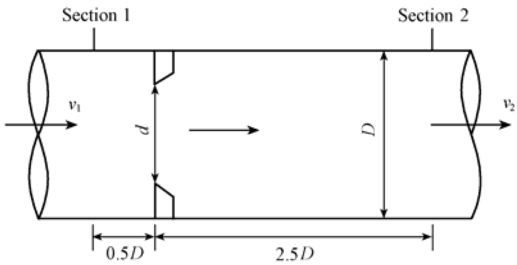

Fig. 1 Theoretical analysis model

The theoretical analysis model is shown in Fig. 1, where *d* and *D* are, respectively, the diameter and inner diameter of the orifice and pipe. Considering the incompressible steady flow in an orifice energy dissipator, cross-section 1 is determined to be 0.5*D* in front of the orifice, and cross-section 2 is 2.5 *D* behind it. The flow through cross-sections 1 and 2 is fully developed flow, and the velocity distribution profiles are the same, so the kinetic energy correction coefficients of the two cross-sections, α_1 and α_2, are constants equal to one. The continuity and momentum equations between cross-sections 1 and 2 can be described as follows:

$$Q = A_1 v_1 = A_2 v_2 \tag{1}$$

$$p_2 A_2 - p_1 A_1 = \rho Q\left(v_1 - v_2\right) \tag{2}$$

where Q is the flow rate; A_1 and A_2 are the areas of cross-sections 1 and 2, respectively; v_1 and v_2 are the fluid velocities at two cross-sections; p_1 and p_2 are the average water pressures at two cross-sections; and ρ is the fluid density. The energy loss can be obtained:

$$\Delta E = \left(\frac{p_1}{\rho g} + \frac{\alpha_1 v_1^2}{2g}\right) - \left(\frac{p_2}{\rho g} + \frac{\alpha_2 v_2^2}{2g}\right) = \frac{p_1 - p_2}{\rho g} + \frac{1}{2g}\left(\alpha_1 v_1^2 - \alpha_2 v_2^2\right) \tag{3}$$

where g is the gravitational acceleration. With the assumption that the pressure distribution at the cross-sections obeys the principle of hydrostatic pressure, Eqs. (1) through (3) are combined and rearranged. ΔE can be further described as

$$\Delta E = \frac{p_1 - p_2}{\rho g} \tag{4}$$

In order to identify the factors affecting the efficiency of the orifice energy dissipator, dimension analysis is performed to simplify the problem. The following function (Bushell et al. 2002) is assumed:

$$f(D, d, \rho, \mu, v, \Delta p, L) = 0 \tag{5}$$

where μ is the fluid viscosity, Δp is the pressure drop, L is the spacing between two orifices, and v is the fluid velocity.

According to the $\prod$ theorem and the principle of dimensional homogeneity, the parameters D, v, and ρ are defined as basic dimensions. This problem can be described in the $\prod$ equations as follows:

$$\Pi_1 = \frac{d}{D},\ \Pi_2 = \frac{\mu}{\rho v D},\ \Pi_3 = \frac{\Delta p}{\rho v^2},\ \Pi_4 = \frac{L}{D} \tag{6}$$

The functional relationship can be written as

$$f\left(\Pi_1, \Pi_2, \Pi_3, \Pi_4\right) = f\left(\frac{d}{D}, \frac{\mu}{\rho v D}, \frac{\Delta p}{\rho v^2}, \frac{L}{D}\right) = 0 \tag{7}$$

The complete dimensionless relation for this problem is

$$\Delta p = \rho v^2 f_1\left(\frac{d}{D}, \frac{\mu}{\rho v D}, \frac{L}{D}\right) = \rho v^2 f_1\left(\frac{d}{D}, \frac{1}{Re}, \frac{L}{D}\right) \tag{8}$$

The energy loss between cross-sections 1 and 2 is described as

$$\Delta E = \frac{\Delta p}{\rho g} = \frac{v^2}{g} f_1\left(\frac{d}{D}, \frac{1}{Re}, \frac{L}{D}\right) = \frac{v^2}{2g} f_2\left(\frac{d}{D}, Re, \frac{L}{D}\right) = K\frac{v^2}{2g} \tag{9}$$

where $K = f_2\left(\frac{d}{D}, Re, \frac{L}{D}\right)$. It is defined as the coefficient of the orifice energy dissipation, and it directly reflects the efficiency of energy dissipation. The main factors affecting the efficiency of the orifice energy dissipator are Re, d/D, and L/D.

From Eq. (9), we can obtain the following relationship:

$$K = \frac{\Delta E}{v^2/(2g)} \tag{10}$$

According to the pressure distribution in experiments, the head loss can be expressed by the average pressure difference between cross-sections 1 and 2. With Eqs. (4) and (10), the coefficient of the orifice energy dissipator can be expressed as

$$K = \frac{\Delta E}{v^2/(2g)} = \frac{(p_1 - p_2)/(\rho g)}{v^2/(2g)} \tag{11}$$

3 Numerical study

3.1 Mathematical model

In order to simulate the flow in an orifice energy dissipator, it is vital to select a proper turbulence model (Schiestel 1987). In this study, the k - ε two-equation turbulence model (Liu et al. 1993; Qu et al. 2000; Zhang et al. 2004) was applied to simulate the flow in an orifice energy dissipator. The control volume method (Tao 2004) was employed to obtain the discretization equations by integrating the governing equations over each control volume.

The flow in the pipe is considered incompressible, three-dimensional, and viscous. The governing equations include the continuity equation, the momentum equation, the turbulent kinetic energy equation (k equation), and the turbulent kinetic energy dissipation rate equation (ε equation). These equations can be written as follows:

Continuity equation:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{12}$$

Momentum equation:

$$\frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\left(\mu + \mu_{\mathrm{t}}\right)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \tag{13}$$

k equation:

$$\frac{\partial(\rho u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_{\mathrm{t}}}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k - \rho\varepsilon \tag{14}$$

ε equation:

$$\frac{\partial(\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_{\mathrm{t}}}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + C_{1\varepsilon} G_k \frac{\varepsilon}{k} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{15}$$

where u_i and u_j are the components of velocity; $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are coefficients; σ_k and σ_ε are the turbulent Prandtl numbers for k and ε; and the values of these parameters are as follows: $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $\sigma_k = 1.0$, and $\sigma_\varepsilon = 1.3$. The turbulent viscosity μ_{t} is computed by combining k and ε as follows:

$$\mu_{\mathrm{t}} = \rho C_\mu \frac{k^2}{\varepsilon} \tag{16}$$

where C_μ is a coefficient, and $C_\mu = 0.09$. G_k is defined as

$$G_k = \mu_{\mathrm{t}}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j} \tag{17}$$

The boundary conditions (Launder and Spalding 1974; Tian et al. 2005; Xia and Ni. 2003) are as follows: (1) The inflow velocity U_0 and uniform velocity profile form the inlet boundary. (2) The uniform flow condition is the outlet boundary. (3) The wall function and no-slip boundary condition form a wall boundary.

3.2 Model setup

On the basis of previous analytical studies, the main factors that influence K were identified: *Re*, d/D, and L/D. In order to investigate the influence of different factors on K, different numerical models were constructed for each factor: the *Re* model (including an ideal *Re* model and an actual *Re* model), the d/D model, and the L/D model. In the models, only one factor was changed for a series of numerical experiments.

3.2.1 *Re* model

The *Re* model for the investigation of the influence of the Reynolds number is described below. The other models are defined in the same way.

(1) Ideal *Re* model

In order to calibrate the numerical model, an ideal *Re* model was set up. In this model, only *Re* was altered while the other factors remained the same. The general setting of the *Re* model was a 14.5 cm-diameter pipe with a 2 cm-thick orifice. In front of and behind the orifice were 20-cm and 50-cm straight pipes. Flow in front of the orifice was fully developed. The kinematic viscosity was $\gamma = 1.003 \times 10^{-6}$ m^2/s at a temperature 20°C. For different models, slight changes of γ can be made. *Re* was altered within a range of 10^4 to 10^6 in the experiments and the ratio of d/D was set at 0.60, 0.65, 0.70, and 0.75.

(2) Actual *Re* model

To obtain results with practical significance, an actual *Re* model, in which the length unit in the ideal *Re* model was changed from centimeters to meters, was constructed. The corresponding *Re* varied from 10^7 to 10^8.

3.2.2 d/D model

When *Re*, the orifice shape, and L are constant, K depends primarily on changes in d/D. The model in which d/D was varied but other factors were fixed was called the d/D model. The setting of the d/D model was as follows: The pressure pipe and the orifice location were the same as those in the actual *Re* model. The value of d/D varied from 0.5 to 0.8. The mean velocity inside the pipe was 6.92 m/s and the corresponding *Re* of the flow was 10^8.

3.2.3 L/D model

When *Re*, the orifice shape, and d/D are constant, K depends primarily on changes in L/D. The model in which the orifice shape and d/D were fixed but L/D was varied was called the L/D model, and it is shown in Fig. 2:

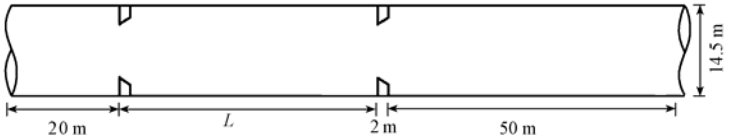

Fig. 2 L/D model

The inner pipe diameter of the pressure pipe with double orifices was 14.5 m. The diameter of each orifice was 10 m and each had a thickness of 2 m. In front of the first orifice, a straight round pipe with a length of 20 m was connected, so that the flow from the front orifice could be fully adjusted. Behind the second orifice was a 50-m straight round pipe. The mean velocity inside the pipe was 6.92 m/s and the corresponding *Re* of the flow was 10^8. L/D varied from 0.5 to 10.

3.3 Calculation results and analysis

3.3.1 Hydraulic characteristics analysis

We used the simulation results for $L/D=3$, as shown in Fig. 3, to analyze the energy dissipation characteristics near orifices. In Fig. 3, l is the distance from the left endpoint of the pressure pipe. The cross-sectional average pressure in the horizontal direction can be seen to have step distribution. Because of the contraction effect of the orifices, part of the flow potential energy transforms into kinetic energy, and the pressure suddenly decreases as flow passes through the first orifice. Later, the flow potential energy gradually recovers, and the pressure curve continues increasing behind the first orifice, which means that the pressure does not completely recover when the flow passes through the second orifice. The same situation occurs as flow passes through the second orifice.

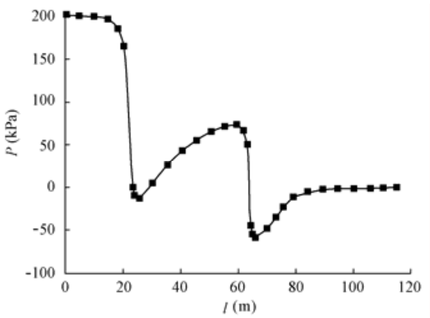

Fig. 3 Pressure distribution along tunnel

The energy dissipation coefficient K of the two orifices was calculated with Eq. (10), and ΔE was calculated based on the difference in water heads at the locations $0.5D$ ahead of an orifice and $2.5D$ behind it. Thus, the energy dissipation coefficients of the first and second orifices were obtained; they were 1.08 and 0.786, respectively. The difference in flow conditions leads to the difference in the coefficients. The inflow at the first orifice is more uniform. Therefore, the contraction effect has full play and affects significant energy dissipation as flow passes through the first orifice. However, because of the contraction effect of the first orifice, the second orifice inflow is concentrated in the middle, which means that the second orifice cannot effectively dissipate energy.

In Fig. 4 it can be seen that hydraulic characteristics are distributed symmetrically along the axis of the pipe. Due to the contraction effect of the orifice, the cross-section of the main flow suddenly decreases and all the hydraulic characteristics change dramatically, with an abrupt increase in velocity and turbulent energy and a decrease in pressure. Taking the center line of the pipe as the axis, the velocity and pressure recover gradually behind the orifice, while the turbulent energy decreases gradually and appears to be low in the middle and high near the pipe wall. Behind the orifice there is a whirlpool region between the main flow and the wall, and strong shear stress exists between the whirlpool and main flow regions, which leads to the conversion of kinetic energy to thermal energy. Then, flow energy dissipates as the thermal energy disappears.

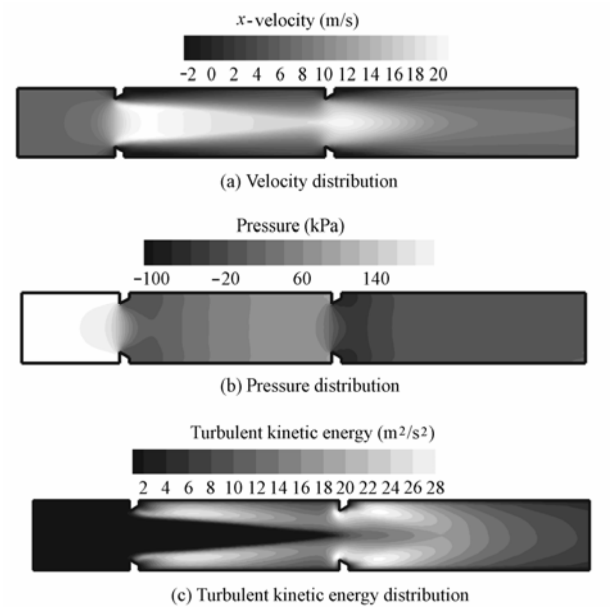

Fig. 4 Hydraulic factor distribution

3.3.2 Total model results

(1) *Re* model results

(a) Ideal *Re* model results:

Fig. 5 shows the relationship between *Re* and *K* for different values of d/D. When *Re* is less than 10^5, the turbulent flow is not fully developed, and the hydraulic factors vary intensely. Under such conditions, *K* increases significantly with increase of *Re*. When *Re* is larger than 10^5, the turbulent flow can be considered fully developed, and the change in hydraulic factors is very small, which means that *Re* does not impact the energy dissipation coefficient *K*. In Fig. 5 we can see that *K* tends to be stable when *Re* is greater than 10^5.

(b) Actual *Re* model results:

Fig. 6 shows that *K* hardly increases with increases of *Re* for different values of d/D, which supports the results of the ideal *Re* model, where *Re* has no influence on *K* in fully developed flow. As real flow can usually be considered fully turbulent flow, the impact of *Re* is always ignored in hydraulic engineering design.

As shown in Fig. 7, the length L_1 of the recirculation region is defined as a distance from the orifice surface to the zero-velocity point of backflow. Fig. 8 shows the relation between *Re* and L_1. For different ratios of d/D, L_1 increases with *Re*. As the recirculation region is the key area for the exchange of energy and momentum between the main stream region and the recirculation region**,** the longer L_1 is, the greater the energy loss and the value of *K* are.

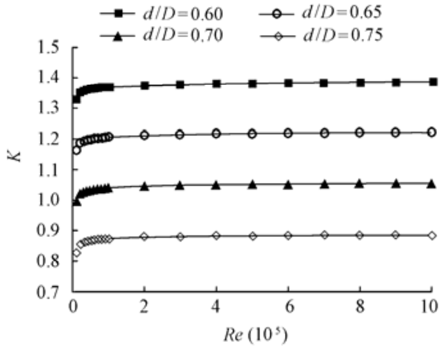

Fig. 5 Relation between *Re* and *K* of ideal *Re* model

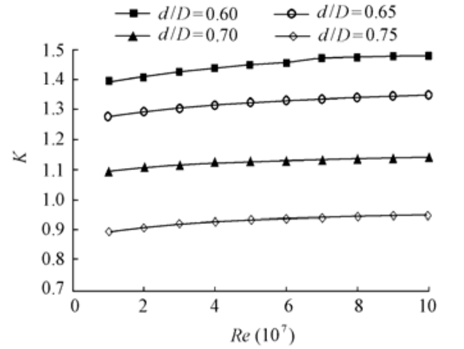

Fig. 6 Relation between *Re* and *K* of actual *Re* model

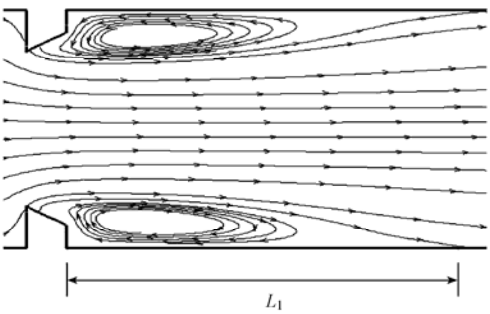

Fig. 7 Sketch of L_1

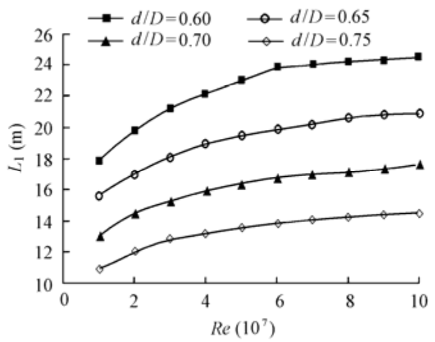

Fig. 8 Relation between *Re* and L_1

(2) d/D model results:

Figs. 9 and 10 show that the length of the recirculation region L_1 and the orifice energy dissipation coefficient K have similar variation patterns. The functions can be approximated as straight lines. As d/D increases, L_1 and K decrease rapidly. The reasons are as follows: With the increase of d/D, the energy conversion between kinetic energy and potential energy becomes smaller. Accordingly, K, which represents the efficiency of energy loss during the process of energy conversion, becomes smaller as well.

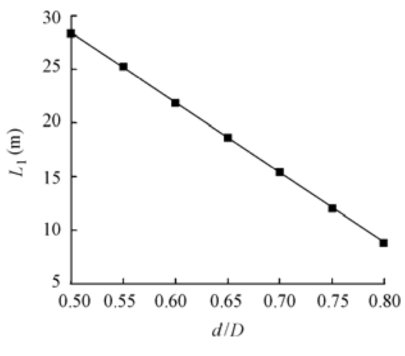

Fig. 9 Relation between d/D and L_1

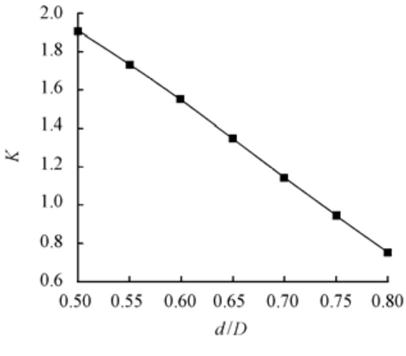

Fig. 10 Relation between d/D and K

(3) L/D model results:

Fig. 11 shows the relation between L/D and K of the whole L/D model. If the distance between the orifices is too short, the recirculation region within that space cannot fully develop. The distribution of hydraulic factors changes intensely, and the total head loss is small. Therefore, the effect on energy dissipation is not very significant. When the distance between the orifices increases, the total head loss increases at the same time. However, when L/D is larger than 5, the recirculation region within the space between two orifices is fully developed. The hydraulic factors vary uniformly. The value of K gradually stabilizes. In contrast to the condition $L/D = 5$, the efficiency of energy dissipation in the condition $L/D = 3$ can reach 95.7% .

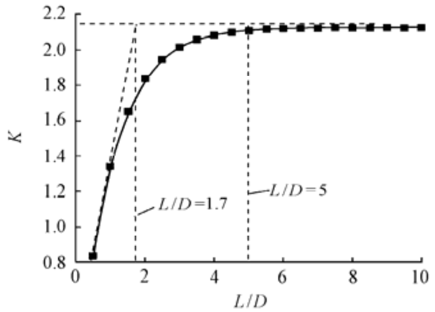

Fig. 11 Relation between L/D and K

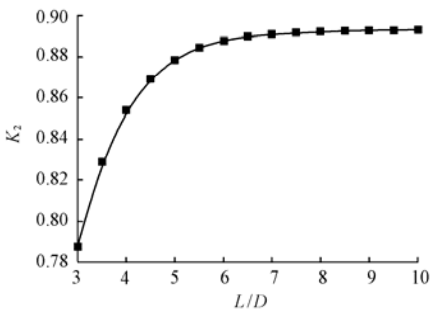

Fig. 12 Relation between L/D and K_2

Simulation results show that the energy dissipation coefficient of the first orifice (K_1) increases rapidly when L/D is less than 1.7, and that K_1 is stable around 1.23, when L/D is larger than 3. Generally, the first and second orifices have different incoming flows. The incoming flow of the first orifice is more uniform and that of the second one is more centralized. Because of this, the coefficient of energy dissipation of the second orifice K_2 is small. Fig. 12 shows the relation between L/D and K_2, demonstrating that it is more difficult for K_2 to reach a stable value. When K_1 reaches a relatively stable value, the variation of K primarily depends on K_2. In Fig. 11 we can see that the K value increases slowly when L/D changes from 1.7 to 5. However, when L/D is larger than 5, the flow velocity and pressure vary slightly within the space between the two orifices (Li 1999) and the recirculation region between the two orifices develops fully; thus, K_2 tends to be steady. Accordingly, the K of the whole L/D model gradually stabilizes and L/D has almost no impact on its value.

4 Conclusions

The main factors that influence the efficiency of the orifice energy dissipator were examined through numerical simulation. The relation between head loss and the factors was investigated.

(1) When Re is less than 10^5, K increases rapidly along with Re. When Re is greater than 10^5, K gradually stabilizes. The recirculation region is the key energy dissipation region. The

shorter L_1 is, the less the energy loss and the K value are.

(2) K is sensitive to the increase of d/D. The relation between K and d/D can be approximated as an inverse relation.

(3) The change in the K value with L/D in the L/D model can be divided into two phases. If L/D is less than 5, K increases rapidly with L/D, but if L/D is larger than 5, K gradually stabilizes, and changes in L/D have almost no influence on both K and K_2.

(4) The numerical results indicate that it is feasible to use a k-ε two-equation turbulence model to simulate the flow in an orifice energy dissipator, and that the orifice energy dissipator is an effective means for energy dissipation.

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