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Minimum wall pressure coefficient of orifice plate energy dissipater

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Abstract

Orifice plate energy dissipaters have been successfully used in large-scale hydropower projects due to their simple structure, convenient construction procedure, and high energy dissipation ratio. The minimum wall pressure coefficient of an orifice plate can indirectly reflect its cavitation characteristics: the lower the minimum wall pressure coefficient is, the better the ability of the orifice plate to resist cavitation damage is. Thus, it is important to study the minimum wall pressure coefficient of the orifice plate. In this study, this coefficient and related parameters, such as the contraction ratio, defined as the ratio of the orifice plate diameter to the flood-discharging tunnel diameter; the relative thickness, defined as the ratio of the orifice plate thickness to the tunnel diameter; and the Reynolds number of the flow through the orifice plate, were theoretically analyzed, and their relationships were obtained through physical model experiments. It can be concluded that the minimum wall pressure coefficient is mainly dominated by the contraction ratio and relative thickness. The lower the contraction ratio and relative thickness are, the larger the minimum wall pressure coefficient is. The effects of the Reynolds number on the minimum wall pressure coefficient can be neglected when it is larger than 10^5. An empirical expression was presented to calculate the minimum wall pressure coefficient in this study.

Keywords: Orifice plate; Minimum wall pressure coefficient; Cavitation; Contraction ratio; Relative thickness; Energy dissipater

1. Introduction

Orifice plate energy dissipaters with sudden-contraction and sudden-enlargement forms have been successfully used in large-scale hydropower projects due to their simple structure, convenient construction procedure, and high energy dissipation ratio. For the Mica Dam in Canada, the flow velocity of the flood-discharging tunnel was decreased from 52 m/s to 35 m/s at the head of 175 m, due to the use of two plugs with lengths of 49 m and 37 m, which are similar to the orifice plate (Russell and Ball, 1967). In the Xiaolangdi Hydropower Project in China, three orifice plates installed in the flood-discharging tunnel obtained an energy dissipation ratio of 44%, and effectively controlled the flow velocity through the gate less than 35 m/s under the condition of a head of 145 m (Ai and Zhou, 2014).

For a flood-discharging tunnel with orifice plate energy dissipaters, the cavitation characteristics of the orifice plate energy dissipater directly affect the safety of the flood-discharging tunnel. Thus, it is necessary to obtain the relationships between the cavitation characteristics of the orifice plate energy dissipater and correlative factors, such as the geometric parameters of the orifice plate and flow conditions. The contraction ratio (β), defined as the ratio of the diameter (d) of the orifice plate to the diameter (D) of the flood-discharging tunnel, is an important index affecting the critical cavitation number of the orifice plate, which can show the cavitation characteristics of the orifice plate (Ai and Wu, 2014). Kim et al. (1998), Takahashi and Matsuda (2001), and Zhang (2003) concluded that the critical cavitation number decreases with the increase of the contraction ratio. Qu et al. (2001), Zhang and Cai (1999), and Ball et al. (1975) indicated that the

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Reynolds number has little impact on cavitation characteristics of orifice plate energy dissipaters.

As stated above, research conducted in the past focused mainly on the effects of the contraction ratio and flow conditions on the cavitation characteristics of the orifice plate energy dissipater based on research of the critical cavitation number of the orifice plate. As a matter of fact, the effects of the orifice plate thickness, which can affect the flow regime around the dissipater and energy loss, on the cavitation characteristics of the orifice plate, are also remarkable. Thus, it is necessary to investigate the effects of orifice plate thickness on the cavitation characteristics of the orifice plate.

Because cavitation around the orifice plate often occurs first at the position of the minimum wall pressure, the minimum wall pressure coefficient of the orifice plate can indirectly reflect the cavitation characteristics of the orifice plate (Zhang and Cai, 1999), and is also an important index for design of the orifice plate (Ai and Ding, 2010). The objective of this study, therefore, was to investigate the effects of all related factors, especially the orifice plate thickness, on the minimum wall pressure coefficient of the orifice plate, to establish an empirical expression for the minimum wall pressure coefficient of the orifice plate, and to analyze the effects of related factors on the cavitation characteristics of the orifice plate.

2. Definition of minimum pressure coefficient

The sketch of the flow through an orifice plate in the flood-discharging tunnel is shown in Fig. 1, where T is the thickness of the orifice plate, and L_b is the length of the vortex-ring region. Vortex-ring regions exist in front of and behind the orifice plate due to the sudden-contraction and sudden-enlargement geometry of the orifice plate, and those vortex-ring regions are the important regions of the energy dissipation. The minimum wall pressure coefficient c_p can be defined as

$$c_p = \frac{p_0 - p_{\min}}{0.5\rho u^2} \tag{1}$$

where p_0 is the pressure on a non-disturbed section in front of the orifice plate, which can be regarded as the section located at least $0.5D$ in front of the orifice plate; $p_{\min}$ is the minimum wall pressure; ρ is the density of water; and u is the average flow velocity in the tunnel. Eq. (1) shows that the smaller $p_{\min}$ is, the larger c_p is, and the more easily cavitation occurs. The minimum wall pressure coefficient c_p shows the status of the minimum wall pressure of the orifice plate. Thus, it can indicate the cavitation characteristics of the flood-discharging tunnel with orifice plates. The larger c_p is, the lower the capacity of orifice plate to resist cavitation damage is.

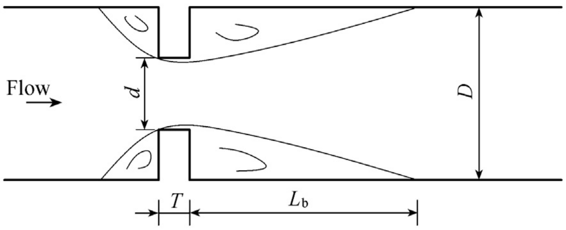

Fig. 1. Flow through orifice plate.

3. Theoretical considerations

The minimum wall pressure coefficient of the orifice plate is related to geometric parameters and hydraulic parameters, including the density of water ρ (kg/m^3), the dynamic viscosity of water μ (N·s/m^2), the tunnel diameter D (m), the orifice plate diameter d, the orifice plate thickness T (m), the average flow velocity in the tunnel u (m/s), and the deviation between the pressure on the non-disturbed section and minimum wall pressure $p_0 - p_{\min}$(Pa). All the above parameters are written into a formula as follows:

$$f_1(D, d, T, \rho, \mu, u, p_0 - p_{\min}) = 0 \tag{2}$$

According to the dimensional analysis, D, μ, and ρ are three basic parameters of the seven. A non-dimensional equation can be obtained using the π theorem as follows:

$$f_2\left(\frac{d}{D}, \frac{T}{D}, \frac{uD\rho}{\mu}, \frac{p_0 - p_{\min}}{\rho u^2}\right) = 0 \tag{3}$$

Eq. (3) can be rewritten as follows:

$$\frac{p_0 - p_{\min}}{\rho u^2} = f_3\left(\frac{d}{D}, \frac{T}{D}, \frac{uD\rho}{\mu}\right) \tag{4}$$

Combining Eq. (1) with Eq. (4), we can obtain

$$c_p = 2f_3\left(\frac{d}{D}, \frac{T}{D}, \frac{uD\rho}{\mu}\right) = f_4(\beta, \alpha, Re) \tag{5}$$

where Re is the Reynolds number; and α is the relative thickness, and $\alpha = T/D$. Eq. (5) indicates that the minimum wall pressure coefficient of the orifice plate c_p is a function of β, α, and Re. The following study procedure was meant to determine the effects of parameters β, α, and Re on c_p, according to Eq. (5).

4. Model experiment

The experimental set-up of the physical model consisted of an intake system, a tank, a flood-discharging tunnel with an orifice plate energy dissipater, and a return system with a rectangular weir (Fig. 2). The diameter (D) of the tunnel model was 0.21 m, and the length of the tunnel model was 4.75 m, i.e., the distance from the intake to the pressure tunnel outlet controlled by a gate was about $22.6D$. The orifice plate energy dissipater was placed at the position of $10.0D$ away from the tunnel intake and $12.6D$ away from the outlet. A water head of about $10.0D$ could be provided by the intake system and the tank. The opening of the gate could be changed conveniently. There were 35 pieces of small plastic tube

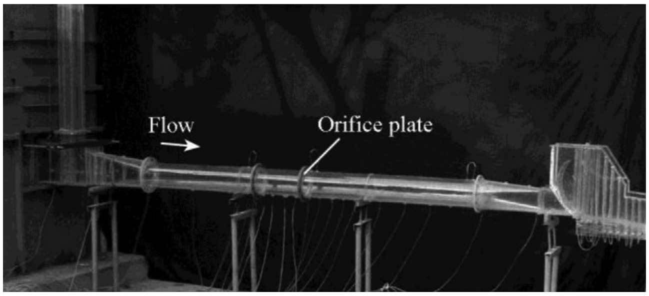

Fig. 2. Experimental model.

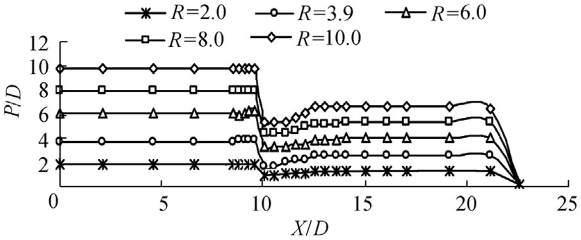

Fig. 3. Wall pressure distributions along tunnel for $\beta = 0.70$ and $\alpha = 0.20$

installed along the tunnel wall, which were utilized to measure the wall pressure. Because flows change violently in the vicinity of the orifice plate, in the region from 0.5D in front of the orifice plate to 4.0D behind the orifice plate, the plastic tubes were densely installed, with a interval of 0.25D. The physical model experiments were conducted at the High-speed Flow Laboratory of Hohai University. The geometric parameters of the orifice plate and flood-discharging tunnel in each case are shown in Table 1.

According to Eq. (5), the effects of the contraction ratio β, relative thickness α, and Reynolds number Re on the minimum wall pressure coefficient c_{p} were examined through physical model experiments. The experiment arrangement was as follows: First, the minimum wall pressure coefficient c_{p} was measured in cases 1 through 5 when β and Re varied and α did not vary, and the effects of the contraction ratio β and Reynolds number Re on the minimum wall pressure coefficient c_{p} were examined; second, the minimum wall pressure coefficient c_{p} was measured in cases 6 through 10 when α and Re varied and β was constant, and the effects of the relative thickness α and Reynolds number Re on the minimum wall pressure coefficient c_{p} were examined.

5. Results and discussion

The measured results of the wall pressure distribution along the tunnel when β is 0.70 and α is 0.20 are shown in Fig. 3, where P is the wall pressure expressed by the height of the water column measured using a piezometer (m), X is the distance from the tank along the flow direction, and R is the ratio of the maximum water level to the diameter of the flood-discharging tunnel. The orifice plate is located between $X = 10D$ and $X = 10.2D$. Fig. 3 shows that the lowest wall pressure occurs in the vicinity of the orifice plate, which approaches the contraction section. The experimental results of the minimum wall pressure coefficient are shown in Table 2 and Table 3.

Table 1
Geometric parameters of orifice plate and flood-discharging tunnel in each case.

Case	β	α	Case	β	α
1	0.40	0.10	6	0.70	0.05
2	0.50	0.10	7	0.70	0.15
3	0.60	0.10	8	0.70	0.20
4	0.70	0.10	9	0.70	0.25
5	0.80	0.10	10	0.70	0.50

It can be seen from Tables 2 and 3 that when the Reynolds number Re is less than 10^5, the minimum wall pressure coefficient c_{p} increases slightly with the Reynolds number Re, but when the Reynolds number Re is more than 10^5, it has no impact on the minimum wall pressure coefficient c_{p}.

Fig. 4 and Fig. 5 are drawn using the data in Tables 2 and 3, respectively, when the Reynolds number is 1.20×10^5. Fig. 4 shows that the minimum wall pressure coefficient c_{p} decreases drastically with the increase of the contraction ratio β when the relative thickness α is constant. Fig. 5 demonstrates that the minimum wall pressure coefficient c_{p} also decreases with the increase of the relative thickness α when the contraction ratio β is constant, indicating that the effect of the relative thickness α on the minimum wall pressure coefficient c_{p} is remarkable, which is often ignored in previous research. From this analysis, it also can be concluded that, the relative thickness α has important effects on the cavitation characteristics of the orifice plate, and the risk of cavitation damage occurring at the orifice plate decreases with the increase of the contraction ratio β and relative thickness α. By fitting the curves in Figs. 4 and 5, the following empirical expression for the minimum wall pressure coefficient of the orifice plate can be obtained:

$$c_{\mathrm{p}} = 1.12\mathrm{e}^{-1.47\alpha}\left(-2.07\beta^2 - 1.70\beta + 3.98\right) \tag{6}$$

This expression is valid for $0.40 \le \beta \le 0.80$, $0.05 \le \alpha \le 0.50$, and $Re > 10^5$.

6. Conclusions

The minimum wall pressure coefficient c_{p} of an orifice plate energy dissipater is a function of the contraction ratio β, the relative thickness α, and the Reynolds number Re of the flow on the basis on Eq. (5). The effects of Re on c_{p} can be neglected when Re is larger than 10^5.

The contraction ratio β and relative thickness α are the key factors that dominate the minimum wall pressure coefficient c_{p}. The lower the contraction ratio β and the relative thickness

Table 2
Variation of c_p with Re and β for $\alpha = 0.10$.

β	c_p				
	$Re = 1.20 \times 10^5$	$Re = 1.10 \times 10^5$	$Re = 1.00 \times 10^5$	$Re = 0.69 \times 10^5$	$Re = 0.51 \times 10^5$
0.40	2.98	2.98	2.97	2.95	2.94
0.50	2.61	2.61	2.60	2.58	2.57
0.60	2.15	2.15	2.14	2.13	2.12
0.70	1.86	1.86	1.85	1.84	1.84
0.80	1.26	1.25	1.24	1.24	1.24

Table 3
Variation of c_p with Re and α for $\beta = 0.70$.

α	c_p				
	$Re = 1.20 \times 10^5$	$Re = 1.10 \times 10^5$	$Re = 1.00 \times 10^5$	$Re = 0.69 \times 10^5$	$Re = 0.51 \times 10^5$
0.05	1.89	1.89	1.87	1.86	1.85
0.10	1.86	1.86	1.85	1.84	1.84
0.15	1.73	1.73	1.72	1.71	1.70
0.25	1.39	1.39	1.38	1.37	1.36
0.50	1.01	1.00	0.99	0.98	0.97

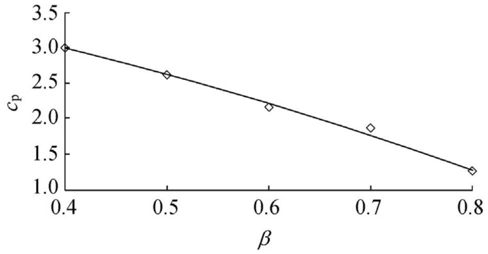

Fig. 4. Relationship between c_p and β for $Re = 1.20 \times 10^5$ and $\alpha = 0.10$

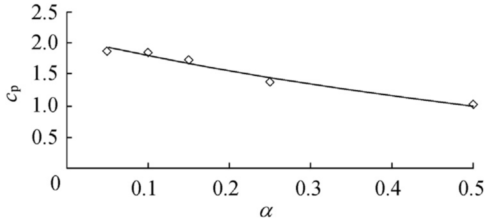

Fig. 5. Relationship between c_p and α for $Re = 1.20 \times 10^5$ and $\beta = 0.70$

α are, the larger the minimum wall pressure coefficient c_p and the risk of cavitation damage occurring at the orifice plate will be. The relationship between c_p, β, and α can be expressed through Eq. (6) when $0.40 \le \beta \le 0.80$, $0.05 \le \alpha \le 0.50$, and $Re > 10^5$.

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