Experimental and CFD study on the optimization of valve lintel’s structural parameters under critical self-aerated conditions

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ABSTRACT
Self-aerated technology of valve lintel (SATVL) is widely used in high head navigation lock water delivery system to address the cavitation problem. To optimize the structural parameters of valve lintel including the height of the throat ($h_1 = 20$ mm) and divergent part enhance ($h_2$), the length of the throat part ($L_2$) and the divergent part ($L_3$), and the diffusion angle ($\beta$) for better self-aerated performance, the dimensionless structural parameters $h_2/h_1$, $L_2/h_1$, $L_3/h_1$ and beta were chosen as the variables. The conception of critical self-aerated conditions was proposed via theoretical analysis and experimental verification for the first time, and the slope $m$ of critical self-aerated conditions was taken as the response to assess self-aerated performance. The method of combing Response Surface Methodology (RSM) with Central Composite Design (CCD) was introduced to systematically investigate the effects of the structural parameters on the self-aerated performance. A 1: 1 full-scale slicing physical model and CFD simulations were designed to capture the critical self-aerated conditions. Finally, though multiple regression analysis, a quadratic polynomial equation between $m$ and structural parameters was obtained. It was found that: (i) the results of theoretical analysis and physical model verification confirmed the hypothesis of critical self-aerated conditions. (ii) with the aid of ANOVA, the sensitivity of structural parameters which influenced critical self-aerated conditions is $F(h_2/h_1) > F(L_3/h_1) > F(\beta) > F(L_2/h_1)$. (iii) the optimal structural parameters are $h_2/h_1 = 1.25$, $L_2/h_1 = 3.5$, $L_3/h_1 = 160$ and $\beta = 2.5^\circ$. The result indicate that the substantial improvement of self-aerated performance can be achieve by using those optimal structural parameters.

Nomenclature

- $k$: turbulent kinetic energy
- $h_1$: the height of the throat (mm)
- $h_2$: the height of the inlet of the divergent part (mm)
- $h_3$: the height of the outlet of the divergent part (mm)
- $L_1$: the length of convergent part (mm)
- $L_2$: the length of the throat part (mm)
- $L_3$: the length of divergent part (mm)
- $m$: the slope of the critical self-aerated conditions
- $P_u$: inlet pressures
- $P_d$: outlet pressures
- $S$: the area of the self-aerated region (m$^2$)
- $V$: the velocity of the fluid (vector) with the subscript being the directional component
- $v_u$: velocity at the inlet part
- $v_d$: velocity at the outlet part
- $v_{th}$: velocity at the throat
- $\alpha$: the angle of the convergent part ($^\circ$)
- $\beta$: the angle of the divergent part ($^\circ$)
- $\gamma$: the volumetric weight of water
- $\xi$: The local hydraulic loss coefficient
- $\varepsilon$: turbulent dissipation rate
- $\nu$: kinematic viscosity
- $\nabla$: del (gradient) operator
- $\nabla^2$: Laplace operator
- $y^+$: Mean non-dimensional distance

1. Introduction

Cavitation in ship lock’s water delivery system causes a series of damages: strong valve vibration and large opening and closing force pulsation; valve panel structural wear and spalling of concrete in flow passage behind the valve. To prevent cavitation damage of high-speed flows, air aeration is one of the most effective ways to solve cavitation problems of hydraulic structures (Aydin & Ozturk, 2009; Bhosekar et al., 2012; Zhang et al., 2011). Compared with forced aeration, self-aeration does not require an additional air compressor or control system and is more suitable for engineering applications, such
as spillway chute aerators (Bhosekar et al., 2012; Bung & Valero, 2018; Chanson, 1989; Pfister & Hager, 2010). As a kind of self-aerated equipment, the self-aerated technology of valve lintel (SATVL) has the advantage of no moving parts, self-aeration, reliable operation, high efficiency of aeration, and corrosion reduction. At present, it has been widely applied in China’s high head ship locks, especially in the rivers with large fluctuations of upstream and/or downstream water levels, such as the Three Gorges Project double way and five-step ship locks.

Valve lintel in the ship locks is composed of the gap and aeration pipes, and Figure 1 illustrates the gap air–water multiphase flow in the self-aerated valve lintel. The basic principle of SATVL can be described as follows: the pressure acting on the valve lintel gap is the pressure difference between upstream and downstream, which decreases as the water level increases in the chamber. As shown in Figure 1(a) and (b), when the valve is opened, high-speed flow leads to the decrease of the gap pressure. Once the gap pressure is lower than the local atmospheric pressure and the turbulent shear stress are large enough (Zhang & Chanson, 2017), air bubbles will be carried into the gap and form the air-aerated jet flow. Then, the high-speed aerated jet flow is mixed with the main stream, making the main stream aerated. It can be seen from Figure 1(c) and (d) that aeration in the valve lintel can deal with both the gap and valve hemline cavitation problem. Thus, SATVL is an advanced technology in solving high-head ship locks hydraulic cavitation problems.

Physical hydraulic model and CFD simulations are widely used to study the cavitation control by aeration problems (Chanson, 1993; Hohermuth et al., 2021; Mosavi et al., 2019; Ramezanizadeh et al., 2019). Generally speaking, the reduced scale-physical hydraulic models suffer from scale effects due to the force rations which are not identical between a model and prototype (Heller, 2011). Pfister and Chanson (2014) stressed the significance of the Froude number (Fr), Weber numbers (We), and Reynolds (Re) to the scale effects of self-aerated flow and introduced the Morton number (Mo) to reduce scale effects. On the other hand, due to the complexity of the air–water multiphase flow, the CFD simulations of air–water flows are still in the developing stage. Although the VOF multiphase flow model and realizable $k – \varepsilon$ turbulent model are the most commonly used models for simulating the air–water two-phase flow (Bayon et al., 2018; Liu & Yang, 2014), and some scholars claim that the simulated results agree reasonably with experimental ones (Bhosekar et al., 2012b; Jothiprakash et al., 2015; Teng & Yang, 2018), Chanson and Lubin (2010) still argued that the verification and certification of the commercial CFD codes were poorly done, and the physical modeling is still the basic tool.

Many studies show that the shape of aeration facilities significantly affects the effect of aeration (e.g. whether it could be self-aerated or not and how much the air can be aerated) (Aydin et al., 2020; Aydin & Oz Turk, 2009). Due to the complexity of the aeration mechanism, the studies about the influence of structural parameters of the aerator on the aeration effect remain imperfect (Bhosekar et al., 2012; Pfister & Hager, 2010). Recent researches have focused on developing measurement and predictive techniques of air concentration (or entrainment ratio (Aydin & Oz Turk, 2009; Yan et al., 2012; Zhang & Chanson, 2017)), while numerous studies have shown that cavitation damage can be greatly reduced as long as air can be aerated: when the air concentration reaches 1% ~ 2%, the cavitation damage can be greatly reduced and completely disappears at 5% ~ 7%. So, the key point of SATVL should focus on whether the valve lintel can be aerated or not, i.e. the critical self-aerated conditions, rather than the aeration concentration. The gap in the valve lintel shown in Figure 1(b) has asymmetry geometry and complicated flow passage structural parameters,
many of which affect the self-aerated conditions. Interestingly, the self-aerated valve lintel was found to be similar to the ejector, which utilizes the venturi effect to draw the secondary flow into the primary flow to form a mixed flow. Similar studies on ejector optimization can be found in previous studies (Ruangtrakoon et al., 2013; Varga et al., 2013). So, SATVL has great potential to be used in aerated corrosion reduction facilities, such as aerated Venturi tube to improve dissolved oxygen in water (Zhang et al., 2018), ejector for refrigeration system (Lin et al., 2013), jet pumps in a steam power plant (Wang et al., 2018), etc. Though remarkable works have been done, the structural parameters of the ejects are still very different due to the difference in working fluid and operating conditions (Wang et al., 2018). To the best of the authors’ knowledge, few studies aim to optimization the structural parameters of such self-aerated equipment. Therefore, a more fundamental analysis of SATVL is of great significance to the design and optimization of similar aeration facilities.

Many structural parameters affect the critical self-aerated conditions, so it is difficult and necessary to study the influence of the structural parameters on the critical self-aerated conditions. For multi-factors analysis, the traditional variable-controlling approach is time-consuming and costly, especially if many variables need to be considered simultaneously. On the other hand, statistically designed technology based on factorial techniques, such as Taguchi methodology (Wu et al., 2018; Ye et al., 2019) and response surface methodology (Archin et al., 2019; Montgomery, 2017; Singh et al., 2019) can be used to reduce the number of experiments and to study the effect of the interaction of variables on the response. In the first category, the orthogonal test method is a widely used method for selecting representative and typical test points from a large number of test points based on statistical mathematics. Wu et al. (2018) studied the structural parameters of steam ejectors by combining CFD simulations with orthogonal tests, which has a great inspiration for this paper. In the second category, RSM, developed by Box and Wilson (Gilmour, 2006), combines the strengths of mathematics and statistics to overcome the limitations of the conventional method by fitting the regression equation to explore the relationship between response and variables (Montgomery, 2017). Hence, it is widely used in the multi-factor optimization problem. The main RSM includes full factorial design, Box–Behnken design (BBD), CCD, etc. Among them, CCD combined RSM technology has been successfully applied in parameter optimization of Chemical reaction parameters (Jourshabani et al., 2015; Zhang et al., 2019).

Optimizing the structure parameters of self-aerated valve lintels to achieve excellent self-aeration performance requires a lot of experimentation. On the one hand, scaled physical models also suffer from unavoidable scale effects and are time-consuming and costly. On the other hand, the air aeration mechanism is not clear yet, and it is difficult to accurately simulate the air concentration utilizing CFD simulations. In this context, the present work aimed to investigate the sensitivity of structural parameters of the valve lintel to the critical self-aerated conditions, to optimize the valve lintel structural parameters to achieve the optimal self-aerated performance. The conception of critical self-aerated conditions was proposed via theoretical analysis and taken as the criterion for evaluating self-aeration performance for the first time. A 1:1 full-scale slice physical model and CFD numerical simulations were established to verify this conception. Then, the slope \( m \) of the critical self-aerated conditions was taken as the desired response instead of air concentration, and RSM and CCD methodology was introduced to study the sensitivity of structural parameters to \( m \) systematically. Finally, the optimal structural parameters were obtained by ANOVA and regression analysis. And Figure 2 is the general flow chart representing the optimization of the structural parameter of the valve lintel.

2. Theoretical analysis and CCD tests designing

2.1. Theoretical analysis of critical self-aerated conditions

Generally, the gap of valve lintel in the ship locks usually consists of four parts (i.e. the inlet convergent part, the throat part, the outlet divergent part, and the aeration pipes). It is schematically shown in Figure 3, where \( L_1, L_2, \ldots \)
and \( L_3 \) represent the length of the convergent, throat, and divergent part, respectively; \( h_1, h_2, \) and \( h_3 \) represent the height of throat, inlet, and outlet of the divergent part, respectively; \( \alpha \) and \( \beta \) represent the angle of convergent and divergent part.

Firstly, according to the Bernoulli equation, the higher velocity of non-cavitation flow is, the lower pressure is. The air will be sucked in the throat section when the negative pressure occurs, and the critical conditions are that the relative pressure at the throat section reaches 0 Pa, the pressure boundary conditions acting on the gap of the lintel are the critical self-aerated conditions: when the mean relative pressure of the throat section reaches 0 Pa, no cavitation occurs, and the critical conditions are

\[
\begin{align*}
Z_1 &= \frac{(Z_a + P_u/\gamma + \frac{v_u^2}{2/g}) - (Z_th + P_{th}/\gamma + \frac{v_{th}^2}{2/g})}{v_{th}^2/2g}, \\
\xi_2 &= \frac{(Z_{th} + P_{th}/\gamma + \frac{v_{th}^2}{2/g}) - (Z_d + P_d/\gamma + \frac{v_d^2}{2/g})}{v_d^2/2g},
\end{align*}
\]

where \( Z, P, \) and \( v \) are the position hydraulic water head, pressures, and velocity respectively. The subscript \( u, th, \) and \( d \) represent the upstream, throat part, and downstream respectively, \( \gamma \) is the volumetric weight of water. It should be noted that the local hydraulic head loss coefficient, although calculated by Equation (3), is only related to the structural parameters of valve lintel, i.e. \( \xi_1 = \xi_1(L_1, h_1, \alpha), \) and \( \xi_2 = \xi_2(L_2, L_3, h_1, h_2, \beta). \)

When the critical self-aerated conditions occur, \( P_{th}/\gamma \) equals 0. The continuity Equation (2) is substituted into energy Equation (1), then,

\[
\frac{P_u}{\gamma} = \frac{1 + \xi_1 - (h_1/h_1 + L_1 \tan \alpha)^2}{1 - \xi_2 - (h_1/h_2 + L_3 \tan \beta)^2} \times \left[ \frac{P_d}{\gamma} - (L_2 + L_3) \right] - L_1.
\]

Let

\[
m = \frac{1 + \xi_1 - (h_1/h_1 + L_1 \tan \alpha)^2}{1 - \xi_2 - (h_1/h_2 + L_3 \tan \beta)^2},
\]

and then Equation (5) can be finally rewritten as:

\[
\frac{P_u}{\gamma} = \frac{m P_d}{\gamma} - m(L_2 + L_3) - L_1.
\]

It can be seen from Equation (6) that under the critical self-aerated conditions, there is a linear relationship between \( P_u/\gamma \) and \( P_d/\gamma \) with a slope of \( m. \) Particularly,
Equation (5) reveals that \( m \) is a function only related to the structural parameters, which suggests whether the air is aerated or not is closely related to the geometry of the valve lintel.

The critical self-aerated conditions of valve lintel, the red line is graphically shown in Figure 4, divides the \( P_u/\gamma \) and \( P_d/\gamma \) plane into two regions. The upper left and lower right corner of the critical self-aerated conditions line will be termed the ‘Self-aerated region’ and ‘Non-aerated region’, respectively. Because in the upper left corner, the upstream pressure is greater than the critical pressure, and the pressure in the gap is lower than the local atmospheric pressure. Therefore, negative pressure sucks air into the gap, which makes the gap flow self-aerated. Similarly, the lower right region belongs to the ‘non-aerated region’ as the upstream pressure is below the critical pressure and the gap flow velocity magnitude is small while the pressure is high, thus the air cannot be sucked.

In summary, it can be seen that the principle of optimizing the shape of valve lintel is to enlarge the area of self-aerated region \( S \). As shown in Figure 4, with the decrease of \( m \), the new critical self-aerated conditions (blue dotted line in Figure 4) increase the area of the self-aerated region. This means that it is more suitable for the different combined working conditions of water level in ship locks. It is in this spirit that we developed the area of self-aerated region as the response of valve lintel’s geometry optimization, which can be obtained by integrating the critical self-aerated conditions:

\[
S = \int_{0}^{h_u} \left( \frac{P_u}{m \gamma} + (L_2 + L_3) \right) d \left( \frac{P_u}{\gamma} \right), \quad (7)
\]

namely

\[
S = \frac{1}{2m} h_u^2 + \left[ (L_2 + L_3) + \frac{L_1}{m} \right] h_u \approx \frac{1}{2m} h_u^2. \quad (8)
\]

It is evident from Equation (8) that, \( S \) is a dimensional number that is inversely proportional to \( m \) and changes with \( h_u \). On the contrary, \( m \) is a dimensionless number which only related to the structural parameters, and for any \( h_u \), the smaller \( m \) is, the larger \( S \) is. Thus, it is more reasonable to take \( m \) as the response to assess the self-aerated performance.

**2.2. CCD designing and RSM optimization technique**

As stated above, to get good self-aerated performance, \( m \) was taken as the response. It can be seen from the above analysis that \( m \) is a function only related to the structural parameters \( L_1, L_2, L_3, h_1, h_2, h_3, \alpha, \) and \( \beta \). It is necessary to point out that, according to the engineering experience, due to the accuracy of valve installation and the deformation caused by hydrodynamic and temperature loads, \( h_1 \) should not be too narrow, usually 20 mm (Wu et al., 2020). Therefore, it was fixed at the value of 20 mm in this paper. Moreover, the convergence angle \( \alpha \) has little effect on the jet velocity magnitude and the pressure in the throat part, so it was regarded as an insignificant factor and was fixed at 21° in this paper. Finally, four normalized structural factors (i.e. \( h_2/h_1, L_2/h_1, L_3/h_1, \) and \( \beta \)) were chosen as the key influential factors.

In this paper, each of the selected four variables was divided into 3 levels \((-1, 0, +1)\) and the star points of \( \pm 2 \) for \( \pm \lambda \). The actual and coded levels of the structural factors are shown in Table 1. A four-factor face central composite design, the most commonly used second-order model in RSM, was used to optimize those structural parameters. Based on the theory of CCD, all the experimental design involved 4 influential factors 30 experiments calculated by Equation (9). And all the experiment arrangements are listed in Table 4.

\[
N = 2^n + 2n + n_c = 2^4 + 2 \times 4 + 6 = 30, \quad (9)
\]

where \( N \) is the total number of tests, \( n \) is the number of independent variables, and \( n_c \) is the number of replicates at central points.

The relationship between the response value and the independent variable is usually unclear. Therefore, the idea of RSM is to find a suitable regression model to fit the response and the independent variables. In general, the most used second-order polynomial model in RSM
### Table 1. Structural Parameters value range and levels in the CCD of the valve lintel.

| Independent factor | Code | Level                   |
|--------------------|------|-------------------------|
|                    |      | −λ (−2) | Low (−1) | Central (0) | High (1) | +λ (+2) |
| $h_2/h_1$          | A    | 1.0      | 1.25     | 1.50        | 1.75     | 2.0     |
| $L_2/h_1$          | B    | 3.0      | 3.5      | 4.0         | 4.5      | 5.0     |
| $L_3/h_1$          | C    | 8.5      | 11.0     | 13.5        | 16.0     | 18.5    |
| $\beta$ (°)       | D    | 0.0      | 2.5      | 5.0         | 7.5      | 10      |

Note: The values of $\alpha$ is fixed at 21° and $h_1$ is 20 mm in this paper. $\lambda$ is the distance between each axial point and the center point in the CCD design.

**Figure 5.** The 1:1 full-scale slicing model of gap flow in valve lintel: (a) sketch, (b) photo.

The response can be expressed as (Montgomery, 2017):

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i<j} \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \varepsilon,$$

where $y$ is the required response; $\beta_0$, $\beta_i$, $\beta_{ij}$, $\beta_{ii}$ are the coefficients of linear, interaction, and quadratic factor respectively; $x_i$ and $x_j$ are the variable attributed to factor $i$ and $j$; $k$ is the number of factors and $\varepsilon$ is the random error.

### 3. Experimental and numerical preparation

#### 3.1. The 1:1 full-scale slicing physical model

To study the characteristics of critical self-aerated conditions, a 1:1 full-scale (prototype) slicing hydraulic physical model (see Figure 5) was designed for CCD tests. In the slice model, a 120 mm wide gap in the valve width direction was set as the experimental object. The pressure acting on the gap and the air flow in the aeration pipes were measured by pressure gauges and air flow meters respectively. A detailed description of this slicing model was reported in the literature (Wu et al., 2020). Besides, it must be emphasized that, because there are no scale effects, the 1:1 slicing physical model provides a realistic representation of the cavitation, aeration, and especially the critical self-aeration characteristics of the valve lintel gap flow in the prototype model.

#### 3.2. Numerical methods and governing equations

To complement physical model tests, CFD simulations were used to calculate the critical self-aerated conditions. The cavitation models were utilized to calculate the pressure and velocity field in the valve lintel to avoid the complexity of air–water multiphase flow simulations.

##### 3.2.1. Governing equations for cavitation multiphase flow

Reynolds Averaged Navier-Stokes (RANS) simulations are the most widely used method for modeling turbulence flows. The general N-S equations can be used to describe the fluid flow in the valve-lintel shown in Figure 3. The continuity equations for the water-vapor mixture flow are given as follows:

$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \vec{v}_m) = 0,$$

$$\vec{v}_m = \sum_{k=1}^{n} \frac{\alpha_k \rho_k \vec{v}_k}{\rho_m}, \quad \rho_m = \sum_{k=1}^{n} \alpha_k \rho_k,$$

where the subscript $m$ represents the mixture phase and $k$ represents phase $k$, $\vec{v}_m$ is the mass-averaged velocity, $n$ is...
the number of phases, \( \rho \) is the density, and \( \alpha \) is the volume fraction.

The momentum equation of the mixture can be expressed as follows:

\[
\frac{\partial}{\partial t} (\rho_m \bar{v}_m) + \nabla \cdot (\rho_m \bar{v}_m \bar{v}_m) = -\nabla p + \nabla \cdot \left[ \mu_m (\nabla \bar{v}_m + \nabla \bar{v}_m^T) \right] + \rho_m g + \bar{F} + \nabla \cdot \left( \sum_{k=1}^{n} \alpha_k \rho_k \tilde{v}_{dr,k} \tilde{v}_{dr,k} \right),
\]  

(14)

where \( \bar{F} \) is a body force, \( \mu_m \) is the viscosity of the mixture, \( \mu_m = \sum_{k=1}^{n} \alpha_k \mu_k \), \( \tilde{v}_{dr,k} \) is the drift velocity for secondary phase \( k \), and \( \tilde{v}_{dr,k} = \tilde{v}_k - \tilde{v}_m \).

Using RANS is still the main way to solve the hydrodynamic problems, but the corresponding turbulence model should be introduced to close the N-S equations. So far, the \( k-\varepsilon \) turbulence model is the well-tested two-equation model that has been widely used in engineering (Argyropoulos & Markatos, 2015; Ashrafizadeh & Ghassemi, 2015). In this paper, the realizable \( k-\varepsilon \) turbulence model, developed by Shih et al (Shih et al., 1995) was used. This model is very applicable to high-speed multiphase flows, including separation and circulation (Ashrafizadeh & Ghassemi, 2015; Zhang et al., 2018).

### 3.2.2. Cavitating model

In the cavitating flow, the Mixture multiphase model was used to deal with the interaction between the multiphase (the water and the vapor). The following vapor transport (ANSYS, 2014) and bubble dynamics equations (Brennen, 2005) are used to describe the evaporation and condensation processes of water-vapor mass transfer:

\[
\frac{\partial}{\partial t} (\alpha \rho_v) + \nabla (\alpha \rho_v \bar{v}_v) = R_e - R_c,
\]  

(15)

\[
\frac{D^2 \mathcal{R}_b}{Dt^2} + \frac{3}{2} \left( \frac{D\mathcal{R}_b}{Dt} \right)^2 = \frac{P_b - P}{\rho_l} - \frac{4\mathcal{V}_v \mathcal{R}_b - 2\sigma}{\rho_l \mathcal{R}_b^2},
\]  

(16)

where the subscript \( v \) represents the vapor phase. \( \alpha, \rho_v, \bar{v}_v \) are the volume fraction, density, and velocity of vapor respectively. \( R_e \) and \( R_c \) are the growth and collapse mass transfer source terms of the vapor bubble respectively. \( \mathcal{R}_b \) is the bubble (vapor) radius, \( \sigma \) is the surface tension coefficient of the liquid phase, \( \rho_l \) is the liquid density. \( P_b \) and \( P \) are the pressure of bubble surface and the local far-field respectively. The net mass transfer was calculated by the Zwart-Gerber-Belamri caviation model in this paper, and this cavitation model can be written as follows:

\[
\left\{ \begin{align*}
R_e &= F_{\text{vap}} \frac{3\alpha_{\text{nuc}} (1 - \alpha_v) \rho_v}{\mathcal{R}_b} \sqrt{\frac{2}{3} \frac{P_b - P}{\rho_l}}, P \leq P_v \\
R_e &= F_{\text{cond}} \frac{3\alpha_v \rho_v}{\mathcal{R}_b} \sqrt{\frac{2}{3} \frac{P - P_v}{\rho_l}}, P \geq P_v 
\end{align*} \right.
\]  

(17)

where \( \mathcal{R}_b = 10^{-6} \) m, \( \alpha_{\text{nuc}} (= 5e-4) \) is the nucleation site volume fraction. \( F_{\text{vap}} (= 50) \), and \( F_{\text{cond}} (= 0.01) \) are evaporation and condensation coefficient respectively.

#### 3.2.3. Boundary conditions (BC) and numerical settings

The velocity and pressure field of the valve lintel gap flow were studied by ANSYS FLUENT software. The flowing boundary conditions and numerical settings listed in Table 2 were applied to all the CFD simulations:

| Options                      | Settings                      | Note                |
|------------------------------|-------------------------------|---------------------|
| Near Wall Treatment          | The Standard Wall Function    |                     |
| Inlet/Outlet BC              | Pressure-inlet/outlet         | see Figure 5(a)     |
| Pressure-Velocity coupling   | PISO                          |                     |
| Spatial discretization:      | Second-order upwind           |                     |
| momentum equations and       |                               |                     |
| turbulent kinetic equations  |                               |                     |
| Operating pressure (Pa)      | 0                             | Chen et al., 2019   |
| Time step (s)                | 10^{-4}                       |                     |
| Convergence criterion        | 10^{-5}                       |                     |

#### 3.3. Verification of the numerical simulations

As to the CFD simulations, it is difficult to set the upstream and downstream pressure boundary conditions to ensure the calculated throat pressure exactly equals 0 Pa. So, to obtain the critical self-aerated conditions utilizing the CFD method, the numerical simulation strategy is that 5 groups of the upstream pressure were selected to study the changing rules of the lowest pressure in the throat part: Firstly, the upstream pressure \( (P_u, \text{relative pressure}) \) was fixed at the value of 196.20, 249.30, 392.40, 490.50, and 588.60 kPa, respectively. At the same time, the downstream pressures \( (P_d = 0, 49.05, 98.10, 147.15, 196.2, 245.25, 294.30, 343.35, 392.40 \text{kPa}) \) respectively are changed to calculate the lowest pressure value in the throat part \( (P_{\text{th}}) \) corresponding to each upstream pressure. Then, a series of scatter points of \( P_d \) and corresponding \( P_{\text{th}} \) can be obtained. Secondary, changing the upstream pressure and repeat the above calculation process in the same way. In this paper, the B-spline curve was introduced to fit these scatters, and then 5 curves of the relationship between \( P_d \) and \( P_{\text{th}} \) can be obtained. Finally,
the intersection of these five curves with \( P_{th} = 0 \text{ Pa} \) are in the critical self-aerated conditions, thus the critical self-aerated conditions (\( P_d \) versus \( P_u \) when \( P_{th} = 0 \text{ Pa} \)) can be obtained.

The 2D structural parameters of Std. No. 1 (Run 26) was selected as the validation geometry. And the experimental and numerical value of the critical self-aerated conditions of Std. No. 1 are compared for the verification of the numerical simulations: (1) the 1:1 full scale slicing physical model of the geometry of Std. No. 1 (run26) was established in the Key Laboratory of transport technology in navigation building construction, Ministry of Transport, PRC. The critical self-aerated conditions were tested in the test ring introduced in section 3.1. (2) The computational domain and meshes of Std. No. 1 for CFD simulations were shown in Figure 6. To minimize the influences of upstream and downstream, the tube length at both the inlet and outlet of the valve lintel was 50 times the height of the throat part to ensure the flow is fully developed. In addition, the grid density around the throat part was increased to improve the flow resolution of the cavitation multiphase flow. Furthermore, to find a suitable mesh size to strike a balance between computing time and computational accuracy, the grid independence study was carried out through three grids, i.e. the coarse, middle, and fine grids, with a total number of elements of 16594, 23004, and 32175, respectively.

According to the numerical simulation strategy presented above, the \( P_{th} \) was obtained for different combinations of \( P_d \) and \( P_u \). Due to the limitation of the article length, only the case of \( P_u = 588.60 \text{ kPa} \) with the medium grid would be presented in Figure 7. Figure 8 (a) shows all the original scatters and fitted curves for the relationship between the \( P_d \) and \( P_{th} \), from which it can be observed that when the \( P_u \) was fixed (e.g. 588.60 kPa), the \( P_{th} \) gradually decreased with the decreased of \( P_d \), and finally remained constant. That was because when the valve lintel was in the choked cavitation model, the lowest pressure in the throat part was the saturated vapor pressure of water and remained constant (Cioncolini et al., 2016; Wu et al., 2020). Furthermore, Figure 8(a) suggests that the critical downstream pressure corresponding to each \( P_u \) could be calculated when the throat pressure was 0 Pa (the intersection of the dotted black line and each fitting curve). Therefore, the numerical values of the critical self-aerated conditions can be obtained. After calculating, the value of \( y^+ \) (non-dimensional distance from the wall to the first grid point) for all grids were checked and were within the acceptable range \( (y^+ \approx 30 - 300) \), which indicated that the first grid points near to the wall are located in the log-law region, and the CFD simulation results could be used for the next analysis.

Finally, the experimental results of the critical self-aerated conditions were plotted in Figure 8(b) with three different grids CFD simulations. As revealed in experimental results, the \( R^2 \) value of numerical critical self-aerated conditions was close to 1, suggesting that the downstream pressure and upstream pressure had a
Figure 7. Throat pressure of Std. No. 1 (run 26) under $P_u = 588.60$ kPa: (a) $P_d = 539.55$ kPa, (b) $P_d = 490.50$ kPa, (c) $P_d = 441.45$ kPa, (d) $P_d = 392.40$ kPa, (e) $P_d = 343.35$ kPa, and (f) $P_d = 294.30$ kPa.

Figure 8. Comparisons of the critical self-aerated conditions for Std. No. 1 (run 26) between experimental and numerical results: (a) throat pressure (relative pressure) of three different grids corresponding to different upstream and downstream pressures, (b) critical self-aerated conditions between three different grids and experimental result.

significant linear correlation. The results were consistent with the theoretical analysis made in section 2.1. On the other hand, the critical self-aerated conditions calculated by medium and fine grids were consistent with the experimental data, and the error of $m$ between them were all less than 5% (see Table 3), which meant that the CFD simulation method was reliable and could be used for the calculation of the critical self-aerated conditions. Furthermore, to achieve a balance between computational consumption and numerical accuracy, the medium grid with about 23 thousand elements was chosen for investigation in this study. And the meshing of the other 23 geometries followed the same principle of this medium-mesh generation.

Table 3. The error of $m$ between experiment and CFD simulations with different grids.

| Mesh       | $m$     | Absolute relative error (%) |
|------------|---------|-------------------------------|
| Coarse grid| 1.753   | 6.31                          |
| Medium grid| 1.753   | 1.15                          |
| Fine grid  | 1.630   | 0.97                          |
| Experimental| 1.649  | -                             |

4. Results and discussion

4.1. The slope $m$ of the critical self-aerated conditions

In this paper, the experimental design of the four-factor three-level CCD was conducted using Design-Expert
Table 4. Central Composite Design (CCD) with variables and observed response values Matrix.

| Std. No. | Run No. | $h_2/h_1$ | $L_2/h_1$ | $L_3/h_1$ | $\beta$ (°) | Actual (tests) $m$ | Predicted $m$ (Equation (18)) |
|---------|---------|-----------|-----------|-----------|-------------|---------------------|-----------------------------|
| 1       | 26      | 1.25      | 3.5       | 11.0      | 2.5         | 1.630               | 1.620                       |
| 2       | 9       | 1.75      | 3.5       | 11.0      | 2.5         | 2.052               | 2.044                       |
| 3       | 10      | 1.25      | 4.5       | 11.0      | 2.5         | 1.793               | 1.816                       |
| 4       | 7       | 1.75      | 4.5       | 11.0      | 2.5         | 1.575               | 1.644                       |
| 5       | 25      | 1.25      | 3.5       | 16.0      | 2.5         | 1.746               | 1.781                       |
| 6       | 12      | 1.75      | 3.5       | 16.0      | 2.5         | 1.907               | 1.897                       |
| 7       | 16      | 1.25      | 4.5       | 11.0      | 7.5         | 1.541               | 1.489                       |
| 8       | 24      | 1.75      | 4.5       | 11.0      | 7.5         | 1.793               | 1.764                       |
| 9       | 22      | 1.25      | 3.5       | 11.0      | 7.5         | 2.052               | 2.044                       |
| 10      | 17      | 1.75      | 4.5       | 11.0      | 7.5         | 1.575               | 1.644                       |
| 11      | 20      | 1.25      | 4.5       | 11.0      | 7.5         | 1.746               | 1.781                       |
| 12      | 19      | 1.75      | 4.5       | 11.0      | 7.5         | 2.052               | 2.044                       |
| 13      | 21      | 1.25      | 3.5       | 16.0      | 2.5         | 1.541               | 1.489                       |
| 14      | 27      | 1.75      | 3.5       | 16.0      | 2.5         | 1.746               | 1.781                       |
| 15      | 14      | 1.25      | 4.5       | 11.0      | 7.5         | 1.793               | 1.816                       |
| 16      | 4       | 1.75      | 4.5       | 11.0      | 7.5         | 2.052               | 2.044                       |
| 17      | 2       | 1.00      | 4.0       | 13.5      | 5.0         | 1.541               | 1.489                       |
| 18      | 15      | 2.00      | 4.0       | 13.5      | 5.0         | 1.793               | 1.764                       |
| 19      | 11      | 1.50      | 3.0       | 13.5      | 5.0         | 2.052               | 2.044                       |
| 20      | 8       | 1.50      | 5.0       | 13.5      | 5.0         | 1.746               | 1.700                       |
| 21      | 3       | 1.50      | 4.0       | 8.5       | 5.0         | 1.801               | 1.859                       |
| 22      | 5       | 1.50      | 4.0       | 18.5      | 5.0         | 1.698               | 1.665                       |
| 23      | 23      | 1.50      | 4.0       | 13.5      | 10.0        | 1.654               | 1.631                       |
| 24      | 28      | 1.50      | 4.0       | 13.5      | 10.0        | 2.044               | 2.091                       |
| 25      | 1       | 1.50      | 4.0       | 13.5      | 5.0         | 1.734               | 1.742                       |
| 26      | 29      | 1.50      | 4.0       | 13.5      | 5.0         | 1.707               | 1.742                       |
| 27      | 13      | 1.50      | 4.0       | 13.5      | 5.0         | 1.716               | 1.742                       |
| 28      | 30      | 1.50      | 4.0       | 13.5      | 5.0         | 1.738               | 1.742                       |
| 29      | 18      | 1.50      | 4.0       | 13.5      | 5.0         | 1.767               | 1.742                       |
| 30      | 6       | 1.50      | 4.0       | 13.5      | 5.0         | 1.792               | 1.742                       |

Note: Std.: Standard run order, the run order is based on CCD, and $h_1 = 20$ mm.

software, and the relationship between factors and responses was analyzed using RSM. A series of CFD simulation tests were conducted according to the experiment matrix given in Table 4, and the CFD simulation strategy is the same as discussed in Section 3.3. It may be mentioned that the CFD simulations can’t carry out repeat tests, so one center point and its five replicates (Std. No. 25-30) were carried out through the 1:1 slicing physical model. In all the replicates, all the experimental conditions of the physical model were re-created instead of repeating measurements for one test, which ensures a more accurate estimate of the overall process error. Finally, all the corresponding test results of $m$ are listed in Table 4.

4.2. Statistical analysis for four-factor three-level design

The RSM combined CCD was used for quantitative analysis of between $m$, $h_2/h_1$, $L_2/h_1$, $L_3/h_1$, and $\beta$. To fit the numerical data to the appropriate mode, four different models (i.e. linear, two-factor interaction (2-FI), quadratic and cubic equations) were considered in this paper. The results of the adequacy comparison of the different models are listed in Table 5. It can be seen that the P-value of both linear and quadratic models is less than 0.01. On the other hand, models with a significant lack of fit should not be used for predictions. A lack of fit P-value > 0.01 indicates that the lack of fit of the model is non-significant, i.e. data fit well with the model (Gülüm et al., 2019). In this paper, the lack of fit P-value for the linear and quadratic models were 0.0015 and 0.0646, respectively. Thus, the quadratic model was chosen as the most suitable model.

As discussed above, when the quadratic model was adopted to fit the test data, the final regression expression, in terms of coded factors, can be written as:

$$m = 1.74 + 0.22A - 7.191 \times 10^{-3}B - 0.048C + 0.11D - 0.048AB - 0.024AC + 0.077AD + 0.028BC - 9.422 \times 10^{-3}BD + 0.013CD + 0.089A^2 - 7.014 \times 10^{-3}B^2 + 4.827 \times 10^{-3}C^2 + 0.030D^2,$$

where $m$ is the slope of the self-aerated condition region, A, B, C, and D are the coded factors listed in Table 1. Additionally, it should be noted that within the application conditions ($\alpha = 21^\circ$ and $h_1 = 20$ mm, $h_2/h_1 \in [1, 2]$, $L_2/h_1 \in [3.0, 5.0]$, and $L_3/h_1 \in [8.5, 18.5]$), Equation
Table 5. Adequacy comparison of the different models.

| Source        | Sequential P-value | Lack of fit P-value | Adjusted R² | Predicted R² | Remarks |
|---------------|--------------------|---------------------|-------------|--------------|---------|
| Linear        | < 0.0001           | 0.0015              | 0.7343      | 0.6567       | -       |
| 2-Factor (two-factor interaction) | 0.1746 | 0.0019 | 0.7727 | 0.6991 | - |
| Quadratic     | < 0.0001           | 0.0646              | 0.9531      | 0.8716       | Suggested |
| Cubic         | 0.0433             | 0.2700              | 0.9818      | 0.7383       | Aliased |

Table 6. ANOVA for the RSM Quadratic model of $m$.

| Source of variation | Sum of squares | DF (Degree of freedom) | Mean square | F Value | P-value (Prob > F) | Status |
|---------------------|---------------|------------------------|-------------|---------|--------------------|--------|
| Model               | 1.90          | 14                     | 0.14        | 43.13   | < 0.0001           | significant |
| A:h$_2$/h$_1$       | 1.13          | 1                      | 1.13        | 358.04  | < 0.0001           | |
| B: L$_2$/h$_1$      | 1.241E-03     | 1                      | 1.241E-03   | 0.39    | 0.5395             | |
| C: L$_3$/h$_1$      | 0.056         | 1                      | 0.056       | 17.90   | 0.0007             | |
| D: $\beta$         | 0.32          | 1                      | 0.32        | 100.72  | < 0.0001           | |
| AB                  | 0.036         | 1                      | 0.036       | 11.54   | 0.0040             | |
| AC                  | 9.396E-03     | 1                      | 9.396E-03   | 2.99    | 0.1045             | |
| AD                  | 0.094         | 1                      | 0.094       | 29.80   | < 0.0001           | |
| BC                  | 0.012         | 1                      | 0.012       | 3.91    | 0.0667             | |
| BD                  | 1.42E-03      | 1                      | 1.420E-03   | 0.45    | 0.5119             | |
| CD                  | 2.81E-03      | 1                      | 2.811E-03   | 0.89    | 0.3596             | |
| A$^2$               | 0.22          | 1                      | 0.22        | 69.76   | < 0.0001           | |
| B$^2$               | 1.349E-03     | 1                      | 1.349E-03   | 0.43    | 0.5225             | |
| C$^2$               | 6.390E-06     | 1                      | 6.390E-04   | 0.20    | 0.6587             | |
| D$^2$               | 0.024         | 1                      | 0.024       | 7.64    | 0.0145             | |
| Residual            | 0.047         | 15                     | 3.147E-03   |         |                    | not significant |
| Lack of Fit         | 0.042         | 10                     | 4.214E-03   | 4.16    | 0.0646             | |
| Pure Error          | 5.068E-03     | 5                      | 1.014E-03   |         |                    | |
| Cor Total           | 1.95          | 29                     |             |         |                    |        |

C.V. = 3.06%, $R^2 = 0.9758$, Adj-$R^2 = 0.9531$, and Pred-$R^2 = 0.8716$.

(18) was used to predict the slope of self-aerated conditions $m$ corresponding to various structural parameters, which is only a mathematic fitting and lacks in physical content.

4.3. The analysis of variance (ANOVA)

Analysis of variance (ANOVA) is the most effective method to assess the competence of the quadratic model, and the results of ANOVA are listed in Table 6. From ANOVA, the $P$-value is the most frequently used value for deciding whether a model is statistically significant, and the $P$-value of a significant model should not be greater than 0.05 (0.05 is taken over for indicating the significance or insignificance), and the F-value should be large. In this paper, the model can be seen to be significant at a 95% confidence level (F-value = 43.13, and P-value < 0.0001). The high significance shows the reliability of the fitted model for predicting the slope $m$ of critical self-aerated conditions. Furthermore, F-value and $P$-value can also be used to evaluate the significance of each independent factor that appeared in the model equation. As seen in Table 6, A, C, D, AB, AD, A$^2$ and D$^2$ were significantly influences $m$ (P-value < 0.05), while the others (B, AC, BC, BD, CD, B$^2$, C$^2$, and D$^2$) were not significant. In addition, the significance and validity of the parameter were determined by the F-value, and the parameter that scores the largest F-value proves to be the most significant factor. Ranking the significant factors according to the magnitude of the F-value as follows: A (358.04) > D (100.72) > A$^2$ (69.76) > AD (29.80) > C (17.90) > AB (11.54) > D$^2$ (7.64). It can be conducted that the most crucial factors (linear terms) are determined as A, D, and C due to the low P-value and high F values. In other words, the sensitivity of structural parameter of valve lintel is: $F(h_2/h_1) > F(\beta) > F(l_3/h_1) > F(L_2/h_1)$.

The lack of fit is the amount the model predictions miss the observations. In this paper, the F-value and $P$-value of lack-of-fit were 4.16 and 0.0646 respectively, indicates that the model’s lack of fit is non-significant, i.e. the test data fit well with the model. On the other hand, the $R^2$ value can be used to assess the quality of the fit of the model, in this paper, the Adj-$R^2$ (adjusted-R Squared, = 0.9583) close to 1.0, which is acceptable for the model accuracy.

The tested (CFD) values of the slope $m$ are listed in Table 4 with the predicted ones calculated by Equation (18). The regression plot of tested and Predicted value shows the largest F-value proves to be the most significant magnitude of the F-value as follows: A (358.04) > D (100.72) > A$^2$ (69.76) > AD (29.80) > C (17.90) > AB (11.54) > D$^2$ (7.64). It can be conducted that the most crucial factors (linear terms) are determined as A, D, and C due to the low P-value and high F values. In other words, the sensitivity of structural parameter of valve lintel is: $F(h_2/h_1) > F(\beta) > F(l_3/h_1) > F(L_2/h_1)$.

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The tested (CFD) values of the slope $m$ are listed in Table 4 with the predicted ones calculated by Equation (18). The regression plot of tested and Predicted value of $m$ is shown in Figure 9, and the y = x line shows the perfect fitness. It can be seen that the prediction results coincide fairly well with the numerical ones, with all the absolute relative errors less than 5%. Furthermore, the residuals follow a normal distribution if the normal probability (NP) plot follows a straight line. The NP plot of residuals is plotted in Figure 10 in this
paper, and it can be seen that the NP plot follows a straight line, indicating that the residuals were normally distributed. Therefore, combined with Figures 9 and 10, it can be demonstrated that the proposed model is applicable.

4.4. Effect of structural parameters on m

The following 6 ($C_2^4 = 6$) figures plotted in Figure 11 visualize the three-dimensional response surface between two influential factors and m, while the other two factors remain at the center point.

Specifically, Figure 11(a) shows the effects of $h_2/h_1$ and $L_2/h_1$ on m when the other two variables remain at the center point. It can be seen that the decreasing of both $h_2/h_1$ and $L_2/h_1$ causes to decrease m, and the influence of $h_2/h_1$ is greater than $L_2/h_1$. A similar rule is obtained in Figure 11(c), i.e. the decrease of the $h_2/h_1$ and $\beta$ has a significantly negative effect on m, indicating that $h_2/h_1$ and $\beta$ are the most significant influencing factors of m. Figure 11(b) shows the combined effects of $h_2/h_1$ and $L_3/h_1$ on m. It is evident that $h_2/h_1$ has a significant negative effect on m, while $L_3/h_1$ has a slight positive effect on m. Additionally, the flat 3D surfaces shown in Figure 11(d) and (e) indicate that m does not vary much with the change of $h_2/h_1$ and $L_3/h_1$. Finally, Figure 11(f) shows the coupled effect of $L_3/h_1$ and $\beta$ on m. Qualitatively speaking, according to the Bernoulli equation, the longer the length and the smaller the angle of the divergent part is, the greater the velocity and the lower the pressure at the outlet are. This will help to maintain a sufficient negative pressure zone in the throat part. In other words, the longer the divergent part length and the smaller the angel are, the better the critical self-aerated conditions are, and the smaller m is. It is evident that the effect of $L_3/h_1$ and $\beta$ on m follows those general rules.

4.5. Optimization result and numerical validation.

To obtain the optimum values for the structural parameters of the valve lintel, the optimization criterion is to define m as the minimum value in its design space. As predicted by RSM according to Equation (18), the minimum predicted value of m is 1.489 and the corresponding structural parameters are $h_2/h_1 = 1.25$, $h_2/h_1 = 3.50$, $L_3/h_1 = 16.0$, and $\beta = 2.5^\circ$ (see Table 7).

For validating the RSM optimum result above, the CFD simulation validation tests were applied under the RSM-optimized situations. Similarly, as those discussed in section 3.3, throat pressures of the optimum valve lintel corresponding to different upstream pressure and downstream pressure were obtained utilizing CFD simulations and shown in Figure 12(a). And then the critical self-aerated conditions were obtained (see Figure 12(b)). It can be seen from Table 7 that, for the slope m corresponding to the optimal structural parameters, the CFD simulated value is 1.541 ($R^2 = 0.999$) and the RSM predicted value is 1.489, and the relative error of m between them is 3.42%. It indicates that the CFD simulated value of m is nearly equal to its predicted value calculated by Equation (18). On the other hand, it can be seen from Table 7 that the slope m of the critical self-aerated conditions for the optimal geometry is smaller than the reference geometry, which indicates that the optimal will have better self-aerated performance. Therefore, the optimal structural parameters predicted by RMS are considered reasonable and acceptable.
Table 7. Conclusion of RSM optimization and validation test of the critical self-aerated conditions.

| Variables | Range     | Reference geometry (Center point of CCD) | RSM optimized result | m          |
|-----------|-----------|------------------------------------------|---------------------|------------|
| $h_2/h_1$ | 1.0-2.0   | 1.50                                     | 1.25                | 1.489 (RSM predicted) 1.541 (CFD calculated) 1.742 (Reference geometry) |
| $h_2/h_1$ | 3.0-5.0   | 4.0                                      | 3.50                |            |
| $L_3/h_1$ | 8.5-18.5  | 13.5                                     | 16.0                |            |
| $\beta$ (°) | 0.0-10.0 | 5.0                                      | 2.5                 |            |
5. Conclusions

In this paper, the conception of critical self-aerated conditions was proposed as the criterion for the optimization of valve lintel's structural parameters for the first time. A new way was presented for the design and optimization of structural parameters of valve lintel, and it also has potential application value for optimization of other cavitation control by aeration equipment. The 1:1 full-scale slicing physical models and simulation utilizing the CFD method were designed to obtain the slope $m$ of critical self-aerated conditions $m$ arranged by CCD design, and RSM provided the optimization results. By analyzing the factors which affect the critical self-aerated conditions, make it clear between $h_2/h_1$, $L_2/h_1$, $L_3/h_1$, $\beta$ and $m$. The key observations can be drawn as follows:

1. It is theoretically proved that there is a linear relationship between upstream pressure and downstream pressure under the critical self-aerated conditions:

$$P_u/\gamma = mP_d/\gamma - m(L_2 + L_3) - L_1.$$  

The results of both experimental test and CFD simulation show that the relationship of downstream pressure and upstream pressure presents a significant linear correlation, which is consistent with the theoretical proof. That proves the correctness of the critical self-aerated conditions hypothesis.

2. The slope $m$ of critical self-aerated conditions was taken as the criterion to assess self-aerated performance. The regression equation Equation (18) between $m$ and geometric parameters was established by RSM. Through ANOVA, the primary and secondary factors affecting $m$ are as follows: $F(h_2/h_1) > F(L_3/h_1) > F(\beta) > F(L_2/h_1)$.

3. To get the minimum value of $m$ (i.e. the optimal self-aeration performance), according to the result of optimization analysis of RSM and numerical simulation verification, the optimal valve of lintel’s structural parameters are $h_2/h_1 = 1.25$, $L_2/h_1 = 3.50$, $L_3/h_1 = 16.0$ and $\beta = 2.5^\circ$.

Although the concept of critical self-aerated conditions was first proposed in this study, providing a new angle for optimizing the structural parameters of self-aerated valve lintel, the regression formula in Equation (18) is only a mathematical fitting, and the physical content is insufficient. Artificial neural networks (ANN) methods have good predictive capability and ability, providing an alternative modeling tool to the polynomial regression method. Its modeling of complex relationships, particularly non-linear relationships, can be used in RSM. In future research, the application of ANN in RSM will be able to accurately describe the response surface, even when all structural parameters are considered without simplification and the knowledge of the physical background. Besides, the different working fluids (e.g. air, steam, etc.) can be studied in combination with the concept of critical self-aerated conditions for wider application in the optimization of the aerator structural parameters.

Disclosure statement

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