Opening Angle and Impact Force Analysis of Different Types Flap Valve in Pumping Stations

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Abstract: Based on the energy method, the motion equation of the flap valve is deduced. Combining with the example of Bailizhou Pumping Station, the opening angle and impact force of the flap valve with different forms of installation (free rollover, free suspended, covers), different valve pages (single-leaf and double-leaf) and different materials (steel and composite materials) are analyzed and calculated. Under the same conditions, the results show that: for single-block flap valve of different installations, opening angle of free rollover flap valve is bigger than free suspended flap valve at 22°, and bigger than cover flap valve at 12°, impact force of three installation forms flap valve is close. For different valve pages, opening angle of double-leaf flap valve is slightly larger than the single-leaf, impact force of free rollover double-leaf flap valve is 42% of the single-leaf, and cover double-leaf flap valve is 49% of the single-leaf. Comparing different materials, opening angle of free rollover composite flap valve is 4% bigger than the steel flap valve, its impact force is 9.6% smaller than steel flap valve, and opening angle of free suspended composite flap valve and cover composite flap valve is 10%~15% bigger than their steel flap valve, impact force of free suspended composite flap valve is 39.5% smaller than the steel flap valve, and cover composite flap valve is 28.5% smaller than the steel flap valve.

1. Introduction
Flap valve is an indispensable and important equipment for pumping station. It consists of door page, door hinge, door seat and seal. Flap valve is installed on the door seat through door hinges, which are sealed by rubber and used as buffer measures for closing door pages. When the water pump is opened, the door pages are lifted and discharged by the impulse of water flow. After shutdown, with the rapid decrease of the impulse of water flow, the door pages fall and cut off the water flow due to self-weight. At present, according to the different installation forms, there are three main types of flap valve: free suspended, free rollover and covers. In addition, there are single-leaf, double-leaf and different materials, which have important influence on the running characteristics and hydraulic performance of flap valve.

At present, the main problems concerned about the application of flap valve are: increasing the opening angle of operation period, reducing resistance, reducing energy consumption, reducing impact force when shutting down. In addition, there will be repeated clapping phenomena in the process of
startup, and long clapping will endanger the structure of flap valve and the safety of buildings. So, it has been an important topic for the study of patting doors and engineering design to choose the form of flap valve so as to make them have large opening angle and small impact force.

Based on the energy method, this paper first lists the general equation of the motion of the flap valve. Then take the typical pumping stations as an example, according to different types of flap valves (different forms of installation, different valve pages and different materials, etc.), the opening angle and impact force of flap valve under the same conditions are analyzed and calculated. Through analysis and comparison, their advantages and disadvantages are comprehensively evaluated, and relevant conclusions and suggestions are put forward. The paper has important reference significance for the research and engineering design of flap valve.

2. General equation of flap valve motion

The movement of the flap valve during shutdown can be divided into positive rotation- positive flow and positive rotation- reverse flow. When closing in the positive flow stage, the flap valve is mainly affected by the flow impulse, motion resistance, additional resistance and floating gravity. When closing in reverse flow stage, the flap valve is mainly affected by hydrodynamic pressure, motion resistance, additional resistance and floating gravity. Among them, the moments of the three forces on the door axis are the same in the positive flow and reverse flow stages. Figure 1 is the geometric inclination angle and installation diagram of the flap valve at the exit of the runner, from this, the general equation of the motion of the flap valve can be deduced[1].

![Figure 1. Geometric inclination angle and installation diagram of the flap valve at the exit of the runner.](image)

According to the geometric relationship of Figure 1, the equation of calculating the opening angle of the flap valve can be obtained from the moment balance equation:

- $M_G \sin(\theta + \alpha) - M_E \cos^2 \alpha = 0$
- $\theta = \arcsin \frac{\sin \gamma}{\sqrt{\sin^2 \gamma \cos^2 \delta + \sin^2 \delta}}$
- $M_G = G \sin \beta R \quad \beta = \arccos(\cos \gamma \cos \delta)$
The moments \( M_1, M_R, M_D, M_s, \) and \( M_y \) [3] produced by flow impulse, motion resistance, additional resistance, floating weight and hydrodynamic pressure on the flap valve are obtained in turn, according to the theorem of momentum moment, the equation of motion of the flap valve can be obtained.

\[
\begin{align*}
\bullet \quad J_0 = \frac{d\omega}{dt} &= -M_1 - M_R - M_D + M_2 \quad \text{(Positive Flow Stage)} \quad (2) \\
\bullet \quad J_0 = \frac{d\omega}{dt} &= -M_R - M_D + M_2 + M_y \quad \text{(Reverse Flow Stage)} \quad (3)
\end{align*}
\]

The above two equations can be transformed into second-order differential equations with respect to \( \alpha \), thus the expression of angular velocity of motion when the flap valve closes is obtained. Firstly, the equation (2) is solved to obtain the expression of angular velocity of motion when the flap valve closes, then the closing time \( t \) is approximated by piecewise integral method. If \( t \leq T_B \), the flap valve closes in the positive current stage, getting the closing angular velocity \( \omega_m \). If \( t > T_B \), the flap valve closes in the reverse flow stage, getting the angle \( \alpha_m \) of flap valve at the end of the positive current, by using equation (3), obtaining the closing time \( t' \) of the flap valve from \( \alpha_m \) to 0. Through trial calculation, till the ratio of \( t' \) to \( T_{BC} \) is the same as the ratio of the final action waterhead to the maximum possible action waterhead[3], getting final angular velocity \( \omega_m \).

When there is a buffer rubber and it is arranged in the impact center, the equation for calculating the impact force is:

\[
N = (mP_y - \frac{n}{2}R) + \sqrt{(mP_y - \frac{n}{2}R)^2 + \frac{sE}{l}J_p\omega_m^2} \quad (4)
\]

When the buffer rubber is arranged at any height, the impact force of the flap valve can also be calculated by the following equation[2]:

\[
N = \frac{1}{L_N} (M_y - \frac{1}{2}M_R) + \sqrt{(M_y - \frac{1}{2}M_R)^2 + \frac{sEJ_p\omega_m^2L_N^2}{l}}
\]

In the equation: \( N \) is the maximum impact force of flap valve closure, \( P_y \) is the water pressure outside the door, \( R \) is the resistance of motion, \( m \) is ratio of the distance between the action point of \( P_y \) and the hinge axis of the door to the distance between the impact center and the hinge axis of the door, \( n \) is ratio of the distance between the action point of \( R \) and the hinge axis of the door to the distance between the impact center and the hinge axis of the door, \( s \) is the contact area between the rubber block and the flap valve, \( E \) is elastic modulus of rubber block, \( l \) is the thickness of rubber block, \( J_p \) is the moment of inertia of flap valve considering the effect of additional resistance, \( \omega_m \) is the angular velocity before flap valve closing, \( L_N \) is the distance from the impact point to the hinge axis, \( M_y \) is the moment caused by water pressure on door hinge, \( M_R \) is the moment caused by flow resistance to door hinges.

Above are the general equations for the motion of the flap valve under different installation forms and submerged positive and reverse flow conditions. When the door diameter is fixed and the working conditions are the same, these equations are only functions of dip angle \( \delta \) and \( \gamma \) in Figure 1. Taking different \( \delta \) and \( \gamma \), the motion equation of the door with a specific installation form can be obtained. When \( \delta = 90^\circ \), the equation of motion of the free suspended composite flap valve can be deduced. When \( \delta \neq 0^\circ \) or \( 90^\circ \), the equation of motion of the self-closing free rollover flap valve can be deduced. When \( \gamma = 90^\circ \), the equation of motion of the covers flap valve can be deduced. They are the important basis for the later analysis and calculation.
3. Opening angle and impact force of clapping door with different installation forms

Taking the typical pumping station-Bailizhou pumping station as an example, the station is installed at 4×800kW, the single pump flow is 7.95m³/s, the lift is 8.40m, the efficiency is 87%, the inner diameter of the outlet passage is 2.0m, the flow velocity is 2.53m/s, the unit's rotational inertia is \(J=1152\text{kg} \cdot \text{m}^2\), the rotational speed is 250r/min, the valve diameter is 2.2m, the volume is 0.13m³, the weight is 800kg, the distance between the door top and the hinge axis is 0, and the submerged waterhead is 3.8 m, the maximum possible water head is 5.2 m. According to the above parameters, different \(\theta\) and \(MG\) can be obtained by substituting different \(\delta\) and \(\gamma\) with formula (1). After calculating \(Mc\) when the door runs steadily, the opening angle \(\alpha_0\) of the door with different installation forms can be obtained by trial calculation. Then calculate \(M_1, M_B, M_D, M_2\) and \(M_Y\) of each type of flap valve, by using formulas (2) and (3), the angular velocity \(\omega_0\) of each closed valve is obtained. Finally, the data are substituted into the formula (4) to calculate the impact force of the flap valve with different installation forms.

According to the above methods, the analytical results obtained are shown in Tables 1 and 2.

### Table 1. The calculation results of the opening angle with different installation forms at \(\alpha_0\) (°).

| Installation form of flap valve | \(\sin\beta\) | \(\theta\) (°) | \(M_0\) (kg \cdot m² \cdot s⁻²) | \(\alpha_0\) (°) |
|-------------------------------|--------------|---------------|-----------------|---------------|
| Free-suspended \((\delta=90°)\) | \(\gamma=0\) | 1 | 10 | 7222.6 | 58.0 |
| Free-rollover 1 \((\delta=10°)\) | \(\gamma=0\) | 0.174 | 0 | 1253.56 | 76.0 |
| Free-rollover 2 \((\delta=5°)\) | \(\gamma=0\) | 0.087 | 64 | 629.17 | 80.4 |
| Cover \(\gamma=90°\) | 1 | 90 | 7222.6 | 70.9 |

### Table 2. Closing duration and front-closing angular velocity of flap valves at different opening angles.

| Door axis and door face inclination | Opening angle of flap valve \(\alpha_0=57°\) | Opening angle of flap valve \(\alpha_0=80.4°\) |
|------------------------------------|---------------------------------------------|---------------------------------------------|
| \(\delta/(°)\) | \(\gamma/(°)\) | Close duration \(t/s\) | Angular velocity before closing door \(\omega_q/(s^{-1})\) | Close duration \(t/s\) | Angular velocity before closing door \(\omega_q/(s^{-1})\) |
| 5 | 0 | 0.82 | 1.88 | 0.935 | 2.17 |
| 10 | 0 | 0.82 | 1.90 | 0.930 | 2.19 |
| 90 | 0 | 0.824 | 1.87 | 0.936 | 2.16 |
| 10 | 0 | 0.824 | 1.89 | 0.930 | 2.19 |
| 90 | 0 | 0.871 | 1.81 | 0.945 | 2.11 |
| 10 | 0.871 | 1.83 | 0.939 | 2.13 |
| 90 | 0.844 | 2.08 | 1.465 | 2.11 |

From the above analysis and calculation, we can see that:

(1) According to the calculation results in Table 1, the opening angle \(\alpha_0\) decreases with the increase of the inclination angle of the door axis, therefore, a larger opening angle of \(\alpha_0\) can be obtained by using smaller inclination angle \(\delta\). In comparison, the opening angle of the free suspend flap valve \((\delta=90°)\) is 22° smaller than that of the free rollover flap valve \((\delta=5°)\), this is because when the flap valve is opened, the flow of the free suspend flap valve has to overcome all the gravity to do work, while the flow of the free rollover flap valve only needs to overcome part of the gravity of the flap valve. The opening angle of the cover type flap valve \((\gamma=90°)\) is 12° larger than that of the free suspended flap valve \((\delta=5°, \gamma=10°)\), and about 10° smaller than that of the free rollover flap valve. Under the same conditions, the trend of open angle of the three types of installation is that the open angle of the free rollover flap valve is about 10% larger than that of the cover flap valve, and the open angle of the cover flap valve is about 10% larger than that of the free suspended flap rollover. The larger opening angle can greatly improve the flow condition of the flap valve, thus reducing the flow resistance and energy consumption of the flap valve.
(2) According to the calculation results in Table 2, for the example of Bailizhou Pumping Station, no matter what type of flap valve is used, once shutdown, it can be completely closed in the positive rotation-positive flow stage, and the closure duration $t$ increases slightly with the increase of $\delta$, decreases slightly with the increase of $\gamma$, and the closure angular velocity $\omega_q$ decreases slightly with the increase of $\delta$. The increase of $\gamma$ was slightly increased, but the difference was slight on the whole. According to the expression of impact force when the flap valve closes in the positive rotation-positive flow stage of pump shutdown, it can also be seen that the smaller the angle of $\delta$ placed on the valve, the shorter the closing time, and the greater the angular velocity $\omega_q$ before the valve closes, but the greater the flow impulse when the valve closes correspondingly, the smaller the gravity component perpendicular to the door page, so the trend of the impact force varies with the angle of the valve is not clear. This is different from what people expect.

However, according to the analysis and calculation results of the anhydrous rollover flap valve, it can be seen that [1] (the calculation is consistent with the qualitative analysis results), the main reasons for the above situation are as follows: when the flap valve is submerged, its gravity is much smaller than the hydrodynamic pressure and water resistance (400 times difference), so gravity has little effect on the motion of the flap valve in submerged state, therefore, the improvement effect of free rollover flap valve in submerged state on reducing the impact force of closed door is not obvious.

4. The opening angle and impact force of flap valve with different valve pages

There are two main types of door, single and double. Especially for the large-caliber free-rollover door, two opposite valves are usually used. So what is the effect of single and double blades on the opening angle and impact force of the same caliber free rollover valve? Here we still take Bailizhou Pumping Station as an example for analysis. When the flap valve of the station is changed from a single leaf to a double leaf, the distance between the center of gravity of the flap valve and the hinge axis becomes 0.629 m, and the moment of inertia of the flap valve around the hinge axis is 191 kg/m².

For convenience of comparison, the open angle and impact force of single-leaf free suspended, single/double-leaf free rollover and single/double-leaf cover flap valve are calculated by the above equations. The results are shown in Table 3. Among them, the calculation of the double-leaf valve is carried out for one of them. The method is that, firstly, the moment of buoyancy $M_G$ of a valve around the hinge axis is calculated, then the moment $M_c$ produced by the flow impulse of half of the flow when the door runs stably is obtained. By using formula (1), the opening angle of the double-leaf valve is calculated, and then the moment $M_1, M_2, M_D, M_2$ and $M_Y$ of one of the double-leaf valve in the closing process are calculated. using the formula (1), (2) and Formula (3), the closing angular velocity $\omega_m$ is obtained. Finally, the data are substituted into Formula (4) to obtain the impact force of one of the double-leaf flap valve.

| Installation form and number of door pages | $M_G$(kg·m²·s⁻²) | $\alpha_0$(°) | $t$/s | $\omega_q$(s⁻¹) | N/kN |
|------------------------------------------|-----------------|-------------|-------|-----------------|------|
| Free-suspended                           |                 |             |       |                 |      |
| $\delta=90^\circ, \gamma=10^\circ$      | 7222.6          | 57.0        | 0.871 | 1.810           | 568.22 |
| Free-rollover                            |                 |             |       |                 |      |
| $\delta=5^\circ, \gamma=10^\circ$      | 1398.34         | 79.0        | 0.82  | 1.900           | 590.19 |
| $\delta=5^\circ, \gamma=10^\circ$      | 400.61          | 79.1        | 1.99  | 1.909           | 247.63 |
| Cover                                    |                 |             |       |                 |      |
| $\gamma=90^\circ$                       | 7222.6          | 70.9        | 1.031 | 2.115           | 642.56 |
| $\gamma=90^\circ$                       | 4130.01         | 71.0        | 2.11  | 2.997           | 315.52 |

Note: For double-leaf flap valve, the calculation result in the table is one of the double-leaf valve.

From Table 3, it can be seen that: (1) the opening angle $\alpha_0$ of double-leaf valve is slightly larger than that of single-leaf valve. Because the outflow condition of double-leaf valve is better than that of single-leaf valve when the opening angle is not too different, under the same conditions, double-leaf valve can obtain better outflow conditions and suffer less outflow resistance than single-leaf valve. (2)
As for the impact force of closed door, the impact force of free rollover double-leaf valve is about 42% of that of single-leaf one, and that of well cover double-leaf valve is 49% of that of single-leaf one. Thus, for Bailizhou Pumping Station, the effect of reducing the impact force of the closed door by the free rollover double-leaf flaps valve is better than that of the well cover double-leaf flaps valve. (3) The rotational inertia of double-leaf valve is much less than that of single-leaf valve, and the action points of water flow on single-leaf valve and double-leaf valve are different. The action points of double-leaf valve are closer to the outflow side, which makes the moment of water flow on double-leaf valve is greater than that of single-leaf valve, so double-leaf valve can get larger opening angle and smaller impact force. It can be inferred that for the same aperture and the same conditions, when more than double-leaf valve are used, a larger opening angle and a smaller impact force can be obtained.

5. Opening angle and impact force of different material flapping doors
The materials used to make flap valve can be steel, wood or artificial composites, their influence on the hydraulic characteristics of the flap valve is mainly reflected in the weight of the flap valve(including the floating box flap valve). For comparison, Bailizhou Pumping Station is still taken as an example, and the materials of flap valve are steel and artificial composite materials (the density of composite materials is 1500-2000 kg/m³, the relative density is 1.5-2.0, only 1/4-1/5 of the density of carbon steel, and the proportion of composite materials is 1.8. The influence of different materials on the opening angle and impact force is analyzed under the same caliber and condition. According to the above conditions, the floating weight \( G \) of different material flap valves is calculated by formula (1), then the torque \( MG \) of the floating weight to the door axis is calculated. After calculating the \( M_c \) of stable operation of flap valves, the opening angle \( \alpha_0 \) of different material flap valves under different installation conditions can be obtained by trial calculation. Then \( M_1, M_R, M_D, M_2 \) and \( M_T \) of different materials are calculated. The closing angular velocity \( \omega_m \) is obtained by using formula (2) and formula (3). Finally, the impact force of different materials is calculated by substituting data into formula (4). The calculation results are shown in Table 4.

| Installation form and material of flap valve | \( M_c/\text{(kg} \cdot \text{m}^2 \cdot \text{s}^{-2}) \) | \( \alpha_0/\text{(°)} \) | \( t/s \) | \( \omega_q/\text{(s}^{-1}) \) | \( N/\text{kN} \) |
|--------------------------------------------|---------------------------------|-----------------|--------|-----------------|--------|
| Free-suspended                            | Steel                           | 7222.6          | 57.0   | 0.871           | 1.810  | 568.22         |
| (\( \delta = 90°, \gamma = 10° \))       | Composite materials             | 3826.9          | 65.9   | 1.189           | 1.103  | 343.85         |
| Free-rollover                             | Steel                           | 1398.34         | 79.0   | 0.82            | 1.900  | 590.19         |
| (\( \delta = 5°, \gamma = 10° \))       | Composite materials             | 742.42          | 82.2   | 2.48            | 1.844  | 533.61         |
| Cover                                     | Steel                           | 7222.6          | 70.9   | 1.031           | 2.115  | 642.56         |
| (\( \gamma = 90° \))                     | Composite materials             | 3826.9          | 80.0   | 1.96            | 1.553  | 459.17         |

From the above analysis and calculation, it can be seen that when the composite material with small specific gravity has the same mass as the steel flap valve, the volume of the flap valve will be increased and the floating weight of the flap valve will be reduced. Similarly, under the condition that the volume of the flap valve is constant, the quality of the flap valve will be reduced, and the floating weight of the flap valve will also be reduced. It can be seen from Table 4 that, (1) under the same conditions, the opening angle of the flap valve is larger than that of the steel flap valve when the composite material with small specific gravity is used. Among them, the open angle of composite flap valve is 10%-15% larger than that of steel flap valve, while the open angle of composite flap valve with free-rollover is only 4% larger than that of steel flap valve. This is due to the fact that the moment \( M_c \) of the free-rollover flap valve is much less than that of the free-suspended type and the covers type when the composite material is used, while the moment of the water flow impulse to the door shaft is invariable. Therefore, the opening angle of the free-rollover flap valve is less than that of the free-suspended type and the covers type when the composite material is used. (2) The impact force of composite flap valve is much smaller than that of steel flap valve. Among them, the impact force of free-rollover composite flap valve is 9.6% less than that of steel flap valve, the impact force of free-
suspended composite flap valve is 39.5% less than that of steel flap valve, and the covers composite flap valve is 28.5% less than that of steel flap valve. Among the three installation modes, the impact force of the free-rollover composite flap valve decreases slightly, because the moment $M_G$ of the free-rollover flap valve's floating gravity to the door axis is less than that of the free-suspended flap valve and the covers flap valve, and the change range of the initial closing angle $\alpha_0$ of the free-rollover flap valve is smaller than that of the free-suspended flap valve and the covers flap valve.

6. Conclusion
(1) As far as installation is concerned, comparing the three types of flap valve: free-rollover type, free-suspended type and covers type, the open angle of free-rollover type flap valve is about 10% larger than that of covers type flap valve in normal operation, while the open angle of covers type flap valve is about 10% larger than that of free-suspended type flap valve, therefore, the free-rollover flap valve has the best outflow condition and the least hydraulic loss in normal operation. In terms of impact force, the impact force of the closed door of the three types of installation is similar. Compared with the free-suspended flap valve, the impact force of the free-rollover flap valve is smaller when the free outflow closes, and the impact force is improved when the submerged outflow closes, but the effect is not obvious. The impact force of the closed door of the covers type flap valve changes little with the opening angle of the flap valve, when the opening angle of the covers type flap valve is small, the impact force of the closed door is slightly larger than that of the free-rollover type flap valve and the free-suspended type flap valve.

(2) The single-leaf flap valve has simple structure, but its weight and moment of inertia are relatively large, especially for large diameter flap valve, the impact force will be very large. Therefore, it is not advisable to use single-leaf whole-block type for large-caliber flap valve. Generally, single-leaf type can be used for flap valves with diameter $D < 2000$ mm, and double-leaf type can be used for larger-caliber flap valve. The moment of inertia of double-leaf flap valves is much less than that of single-leaf flap valves[2]. Reducing the moment of inertia of flap valves can reduce the impact force of flap valves. The impact force of double-leaf flap valve with free-rollover is about 42% of that of single-leaf flap valves, and the impact force of double-leaf flap valves with covers is 49% of that of single-leaf flap valves. There is little difference between the opening angle of double-leaf flap valve and that of single-leaf flap valve in normal operation, but the double-leaf flap valve can obtain better outflow pattern and less hydraulic loss than the single-leaf flap valve.

(3) The composite material with small specific gravity can reduce the floating weight of the flap valve when the weight of the flap valve is kept constant, and the moment of inertia of the flap valve can be reduced when the volume of the flap valve is kept constant. Both of these two methods can increase the opening angle of the flap valve and reduce the impact force of the flap valve. As far as the effect is concerned, the effect of free-suspended and covers flap valves is more remarkable. According to the influence of material, it can be inferred that this can be achieved by using lightweight flap valves with small floating weight, such as spherical shells or floating boxes. Generally 800-1000kW units can use spherical shell flap valve because the dimensions of outflow channels is relatively small. Because of its simple structure, uniform force and high strength, the spherical shell flap valve can be made lighter, the middle of the flap valve is an empty stomach structure, which can further reduce the floating weight of the flap valve. For the units above 1000kW, the type of steel beam system should be adopted in the flap valve, and the sides of the whole flap valve should be closed by the panel to make the empty stomach or filling foam material in the stomach.

(4) As far as hydraulic performance is concerned, free-rollover and composite flap valves are worthy of praise, and they are cheap, widely used and safe to operate.

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