Characteristics of Vortex Chamber Oscillation Device*

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Fluidic watering device has been developed, to which self-oscillating phenomena are applied, and which has a very simple structure. This device is named vortex chamber oscillation device. The jet is controlled only by a circular vortex chamber, and self-oscillation occurs due to a pressure difference between the left and right parts of the vortex chamber. By the momentum balance of main jet, the critical pressure difference to switch the jet left and right is calculated. By the difference between the masses of air flowing into the chamber through an air hole and air flowing out accompanying the jet, the time required for reaching the critical pressure is calculated, and the oscillation frequency is determined. This watering device gives appropriate size of water drops and uniform water distribution. This device was successfully used for the Shinkansen to melt snow on the tracks and the roofs of stations.

Key Words : Unsteady Flow, Fluid Vibration, Fluidic Device, Oscillator, Vortex Chamber Oscillation Device, Watering Device, Snow Melting Device, Oscillation Frequency

1. Introduction

Sprinkler is a typical watering device, and is used as fire fighting device for watering automatically at the time of fires and for automatic sprinkling of water on lawns, farmlands and flowerbeds, and besides, it is widely applied for irrigation.

However the sprinkler comprises mechanical moving parts whose constructions are complicated. Therefore, a new idea has been conceived of applying self-oscillating phenomena of a fluidic device using water as an acting fluid, to develop a new type of watering devices having no moving part and a simple construction.

As the self-oscillating circuit of a fluidic device using air, load sensitive type, feedback type, sonic type, etc, have been designed⁽¹⁾. But, there has been no example of using water, and the circuit for air as it is cannot be used for water. Therefore, a very simple-construction fluidic device using a new working

principle applying self-oscillation of water was developed⁽²⁾. This new device was named vortex chamber oscillation device, describing the working principle. This device has only a circular vortex chamber, and no feedback pipe for controlling a main jet, and does not use the coanda effect of a main jet. It has such characteristic that it generates self-oscillation by a pressure difference between the right and left sides of a vortex chamber, and the construction is so simple that wear or breakage is not likely to occur.

In this report, the self-oscillation mechanism of the vortex chamber oscillation device is analyzed, and the characteristics are clarified. The results are compared with the experimental results, and also the application of this device is explained.

2. Nomenclature

A : sectional area of jet m^2
 c : discharge coefficient
 d : diameter of air hole m
 h : height of jet flow m
 J : momentum of jet $kg, m/s^2$
 m_i : inlet mass flow rate of air through an air hole kg/s
 m_o : outlet mass flow rate of air induced by jet kg/s
 p_o : atmospheric pressure (absolute pressure) Pa
 p_i : pressure in vortex chamber (absolute pressure) Pa
 p_{cr} : critical pressure difference for switching jet Pa
 p_s : supply pressure of water Pa
 Q : volumetric flow rate of jet from main nozzle m^3/s
 R : gas constant $m^2/(s^2K)$

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U : mean velocity of jet m/s
 u : flow velocity of air at an arbitrary point in boundary layer m/s
 V : volume of one side of vortex chamber that is separated by jet m³
 v : mean velocity of jet m/s
 α : coefficient of discharge from an air hole
 δ : boundary layer thickness m
 δ^* : displacement thickness of boundary layer m
 ρ : density of water kg/m³
 ρ_0 : density of atmosphere kg/m³
 ρ_1 : density of air in air chamber kg/m³

3. Principle of Self-oscillation

The shape of the vortex chamber oscillation devices is shown in Fig.1. The water supplied from the supply port becomes a jet passing through the nozzle. This water jet flows across the vortex chamber and goes out from the outlet port. As the width of the outlet port is made a little wider than the spreading width of the jet, the jet touches the right or left edge of the outlet port, sticks to its side wall and flows out spreading widely. Then, if the jet touches the left edge, its small portion flows backward along the left side circular wall into the left half of vortex chamber, and a vortex is formed between the left side circular wall and the jet. On the other hand, the right side of jet flows out with the air in the right side of the vortex chamber, and the pressure in this side becomes low. By the pressure difference between both sides of the vortex chamber, the jet deflects to the right. This action is repeated, and stable oscillation is obtained.

The holes in both sides of vortex chamber adjust the time required for producing a pressure difference to cause an oscillation in the vortex chamber, and help the jet to flow out along the wall of the outlet port, thus widening the watering area.

Fig.1 Vortex chamber oscillation device

4. Size of device

The size of this device is shown in Fig.2. The diameter of the vortex chamber is 60mm, and the holes in this chamber are 3mm in diameter. The outlet angle of outlet port is 120°. The width and depth of the nozzle are 3mm, respectively, and its length is 7mm.

5. Theoretical Analysis

5.1 Pressure difference for deflecting jet

The pressure difference that deflects jet is calculated as follows. About the jet that deflects to the left, a circle tangential to the nozzle wall at the left exit end and passing through the left edge of the outlet port is considered, then, the radius of this circle r becomes the radius of curvature of the jet. The radius of curvature r in this case determined by this method is 362mm.

The pressure difference between the left and right sides of vortex chamber to deflect the jet is called a critical pressure difference. Denoting this pressure difference by p_{cr} , from the balance between the centrifugal force acting on jet and the force due to the pressure difference, the next equation is obtained⁽³⁾.

$$p_{cr} = \frac{J}{rh} \quad (1)$$

$$J = \rho v^2 A \quad (2)$$

The jet flow rate from the nozzle is denoted by Q_s . Taking the discharge coefficient as 0.72, we have

$$Q_s = 0.72 A \sqrt{\frac{2(p_s - p_0)}{\rho}} \quad (3)$$

Fig.2 Dimensions of device

As the experiment is performed by adopting the supply pressure ($p_s - p_o$) of 0.3MPa, the discharge velocity is calculated as follows,

$$v = \frac{Q_s}{A} = 17.66 \dots (4)$$

From Eqs.(1),(2) and (4), we have

$$\left. \begin{aligned} J &= 2.79 \\ p_{cr} &= 2.58 \times 10^3 \end{aligned} \right\} \dots (5)$$

5.2 Inlet mass flow rate of air through an air hole

Assuming that an air hole is a throttle, and denoting the coefficient of discharge by α and the diameter of an air hole by d , the mass flow rate m_i becomes,

$$\begin{aligned} m_i &= \alpha \rho_1 \frac{\pi d^2}{4} \sqrt{\frac{2(p_o - p_1)}{\rho_1}} \\ &= 1.11 \alpha \sqrt{\rho_1} d^2 \sqrt{p_o - p_1} \dots (6) \end{aligned}$$

5.3 Outlet mass flow rate of air induced by jet

The air that contacts with the jet in the air chamber of the side on which the outlet port opens to the atmosphere flows out together with the jet. As shown in Fig.3, the velocity distribution on the jet is considered to be a distribution of ($U-u$) approximately, when air flows at the same speed as the jet on a flat plate at rest, the velocity in the boundary layer is assumed to be u . Therefore, the mass flow rate per unit height is the product of the displacement thickness of boundary layer δ^* , velocity U and density ρ_1 . Assuming δ as the boundary layer thickness and y as the vertical distance from the jet, the next equation is obtained by the 1/7th power law of Prandtl.

$$\frac{u}{U} = \left(\frac{y}{\delta}\right)^{1/7} \dots (7)$$

The displacement thickness of boundary layer on jet δ^* becomes,

$$\begin{aligned} \delta^* &= \frac{1}{U} \int_0^{\delta} (U-u) dy = \int_0^{\delta} \left\{ 1 - \left(\frac{y}{\delta}\right)^{1/7} \right\} dy \\ &= \frac{1}{8} \delta \dots (8) \end{aligned}$$

Fig.3 Outlet mass flow rate of air induced by jet

The turbulence boundary layer thickness δ_x at the distance x from the tip on a plate yields the next equation, denoting the velocity of uniform flow by U .

$$\delta_x = 0.37 \left(\frac{\nu}{Ux} \right)^{1/5} x \dots (9)$$

Then, the theoretical outlet mass flow rate of air induced by jet, m , becomes Eq.(10), denoting the boundary layer thickness at outlet port by δ_o and its height by h .

$$m = \frac{1}{8} \delta_o U \rho_1 h \dots (10)$$

Substituting Eq(9) into Eq(10) and taking $\delta_o = 2.38 \times 10^{-3}$ m, $U = v = 17.66$ m/s, $h = 3 \times 10^{-3}$ m and c as the discharge coefficient, the actual outlet mass flow rate m_o becomes Eq.(11).

$$m_o = c q \rho_1 \dots (11)$$

where, $q = 1.57 \times 10^{-6}$ m³/s.

5.4 Oscillating frequency

The oscillating frequency is obtained as follows:

$$m_i - m_o = \frac{d(\rho_1 V)}{dt} \dots (12)$$

$$\rho_1 = \frac{p_1}{RT} \dots (13)$$

Substituting Eqs.(6),(11) and (13) into Eq.(12), we get

$$\begin{aligned} \frac{dp_1}{dt} - 1.11 \alpha d^2 \sqrt{\frac{RT}{V}} \sqrt{p_1(p_o - p_1)} \\ + 1.57 \times 10^{-6} \frac{c}{V} p_1 = 0 \dots (14) \end{aligned}$$

Substituting $\alpha = 0.7$, $c = 0.6$, $d = 3 \times 10^{-3}$ m, $R = 287.1$ m²/(s²K), $T = 293$ K, $V = 4.24 \times 10^{-6}$ m³, $p_o = 9.81 \times 10^4$ Pa into Eq.(14), the next equation is obtained.

$$\frac{dp_1}{dt} - 0.985 \sqrt{p_1(9.81 \times 10^4 - p_1)} + 2.22 p_1 = 0 \dots (15)$$

6. Numerical Analysis

Computing Eq.(15) by the modified Euler method using a computer, the time required for the pressure in the air chamber to reach the critical pressure difference p_{cr} was calculated. The flow chart is shown in Fig.4.

The result of numerical analysis shows the time t to reach p_{cr} is 1.3×10^{-2} s, and the oscillating frequency is 77Hz.

7. Experimental Apparatus

The experimental apparatus is shown in Fig.5. Water which is pumped up from a water tank passes through the nozzle for

flow rate measurement, and is supplied to the vortex chamber oscillation device. The supply pressure is set at the determined pressure by a pressure gauge.

The pressure in the vortex chamber is measured by semiconductor pressure transducers (Fig.6) that are set at the position facing the air holes.

Figs.7 and 8 show the watering scene using this device. As seen in the figures, the angle of spread in watering is 120° , the size of water drops is adequate, and the distribution of water is almost uniform.

Fig.4 Flow chart

Fig.5 Testing apparatus

Fig.6 Semiconductor pressure transducer

8. Experimental Results

Fig.9 shows a part of the output pressure difference waveform recorded by the pressure transducers. This figure shows that the oscillating frequency is about 75Hz and the critical pressure difference, $2.5 \times 10^3 \text{ Pa}$ is obtained from the right and left output signals using a computer. These values agree well with the analysed values.

Fig.7 Device in watering

Fig.8 Watering scene using this device

Fig.9 Change of pressure in vortex chamber

9. Application

9.1 Snow melting equipment for the Shinkansen⁽⁴⁾

The sprinkler is used for watering on snow to prevent it from flying up in the snowy districts of Sekigahara of Tokaido Shinkansen as the countermeasure against snow damage. Recently, on Tohoku Shinkansen, for the purpose of melting snow by watering more quickly, the vortex chamber oscillation devices were adopted for watering device with very good results.

Fig.10 shows the watering method on the Shinkansen tracks. Fig.11 is a photograph of actual watering on tracks, and Fig.12 is a photograph of the Shinkansen tracks after snow is melted by watering.

9.2 Melting snow on roofs

In the northern districts of Japan, there is much snow in winter, and it is hard work to remove the snow deposit from roofs. The vortex chamber oscillation devices were installed on roofs for melting snow with satisfactory results. The fluidic watering device has the advantage to remove snow by exciting self-oscillation even under snow.

Fig.13 shows the snow melting equipment with watering devices attached on the roof of a Shinkansen station. Fig.14 shows the actual watering scene by the fluidic watering devices.

Fig.10 Watering method on Shinkansen tracks

Fig.11 Watering on Shinkansen tracks

Fig.12 Shinkansen tracks after snow has been melted

(a) plan

(b) elevation

Fig.13 Snow melting equipment of watering devices on the roof of Shinkansen station

Fig.14 Watering scene on a roof

10. Conclusions

This study was done for the purpose to make clear the characteristics of the vortex chamber oscillation device by theoretical and experimental methods, and the following conclusion has been obtained:

(1) The analysis indicates very good agreement with the experimental results regarding the oscillation frequency and the critical pressure difference, and the validity of this analytical method is proved.

(2) It is clear that the following advantages appear, when the newly developed vortex chamber oscillation device is used as a watering device.

- (i) It has no moving part.
- (ii) Wear and breakage are not likely to occur.
- (iii) The construction is simple, and the cost is low.
- (iv) The size of water drops is

appropriate, and the distribution of spraying drops is uniform.

(3) Good results are obtained when the snow melting equipment is used for the tracks and roofs of Shinkansen.

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