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The Structure of Wheel Check Valve Influence on Air Block Phenomenon of Piezoelectric Micro-Pump

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Abstract: To improve the stability and reliability of the piezoelectric micro-pump, the cause of air block phenomenon is analyzed on the structure of wheel check valve. During the movement of the bubble in the micro-channel, pressure drop occurs, the main factor which influences the bubble going through is opening height of the wheel check valve. Five groups of wheel check valves with different structures are used to test the wheel check valve opening height and air block probability. The experiment results show that reducing the wheel check valve thickness or diameter ratio can both increase the wheel check valve opening height, and decrease the air block probability. Through experiment, the optimum combination of the wheel check valve structure is obtained within the samples: as the thickness is 0.02 mm, the diameter ratio is 1.2, the wheel check valve opening height gets 252 μm, and within the given bubble volume, the air block probability is less than 2%.

Keywords: wheel check valve; air block; opening height; equivalent stiffness

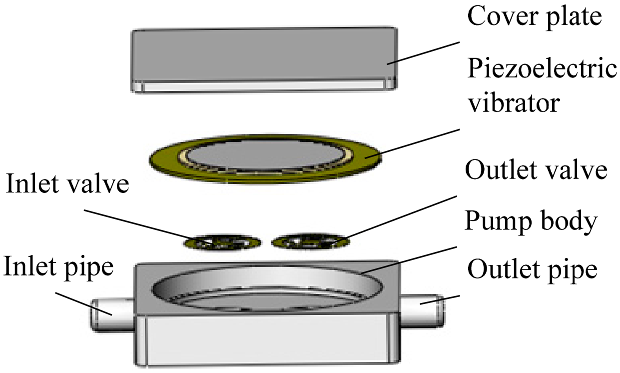
1. Introduction

The piezoelectric vibrator can transfer electric energy into mechanical deformation, and the piezoelectric micro-pump (shorten as "micro-pump") with vibrator has small volume, low power consumption, easy for flow control, *etc*. The experiment shows that in pure liquid condition or pure air condition, the micro-pump can both work well, however, when micro-pump works in the air-liquid mixed fluids, it easily fails [1]. Two main sources for bubble gets into the pump: The air mixed into the input pipe, e.g., the bubbles caused when adding, changing or sloshing the liquid gets directly into the pump channel; the micro-air mass dissolved in liquid changes into micro-bubbles under the changes of the ambient temperature or the alternating pressure, and the micro-bubbles grow, combine to obvious volume bubbles. The failure caused by bubbles show as the bubbles get into the pump channel, the channel is blocked in random, the piezoelectric vibrator can vibrate normally, but the pump can not convey fluid any more. The channel block caused by bubbles is normally called "air block", which has bad influences on the stability and reliability of the output capacity of the pump, and greatly restricts the application of the pump. In recent years, researchers domestic and aboard gradually recognize the bad effects on the pump performance from bubbles, and the bubble exclusion capacity is set as one important factor for pump design [2–5]. To increase the bubble exclusion capacity of the pump, different measures was selected, e.g., reducing the dead volume, increasing the stroke of micro actuators [6–10], increasing the number of the vibrator [11,12], *etc.* which greatly increase the pump self absorption pressure and flow rate, in some extent, the bubble exclusion capacity is also improved. However, even if the pump works far less than its self absorption pressure loading range, the air block still exists. The micro-pump manufactured in this paper is used as the experimental object, during normal working process, the flow and output pressure are 10 mL/min and 15 kPa, when air block happens, there is no flow or output pressure, the micro-pump can not work. The existence of the air block phenomenon hinders the pump application and extension, to avoid the air block is the necessity to improve the stability and reliability of the pump.

The air block phenomenon of micro-pump is investigated in this paper, and the mechanism is mainly described, through fluid mechanics and structure mechanics, the relationship between the wheel check valve structure and the air block phenomenon is analyzed. Based on theoretical analysis results, measurements on reducing air block probability are presented.

2. Air Block Phenomenon

Figure 1a shows the micro-pump structure, which consists of cover plate, piezoelectric vibrator, inlet wheel check valve (shorten as valve), outlet valve, pump body, inlet pipe and outlet pipe. The vibrator, pump body and the two valves build up a closed chamber. When the vibrator has reciprocating vibration, the pump chamber volume changes as well, the two valves open and close periodically, the sucking process and discharging process are created. During sucking process, the chamber volume increases, the inlet valve opens, outlet valve closes, the fluid gets into the chamber; during the discharging process, the chamber volume decreases, the outlet valve opens, inlet valve closes, the fluid gets out of the chamber. Cycle by cycle, the flow reaches in one direction [4,13–16].



(a)

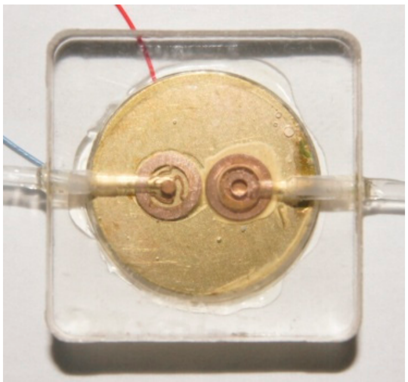

(b)

Figure 1. Micro-pump for experiment. (**a**) Micro-pump structure; (**b**) Micro-pump used in the experiment.

As the bubbles get into the pump chamber, because of the tiny and complicated structure of the channel in the valve, the bubbles easily stay around valve, as shown in Figure 2, white mark is made to recognize the bubble boundary. At this time, the output flow of the pump reduces sharply, unless the bubble gets through the channel and excluded. However, if the bubble is not excluded, and the external load increases slightly, the flow output of the pump will be easily stopped, this is how the air block happens. When the working medium is pure air, the loading capacity of the pump in this paper is 5 kPa, it reaches 25 kPa as the working medium is pure liquid. However, even if the load is below 5 kPa, with air-liquid mixture as the working medium, the air block may happen. The experiment shows that as air block happens, in most cases, the bubbles are either around inlet valve or outlet valve. As air block happens, even with a positive pressure working in the pump inlet valve, as shown in Figure 3, the air block can not be solved, unless the positive pressure is high enough. Based on this condition, the air block is caused by the combination of bubble, liquid and check valve.

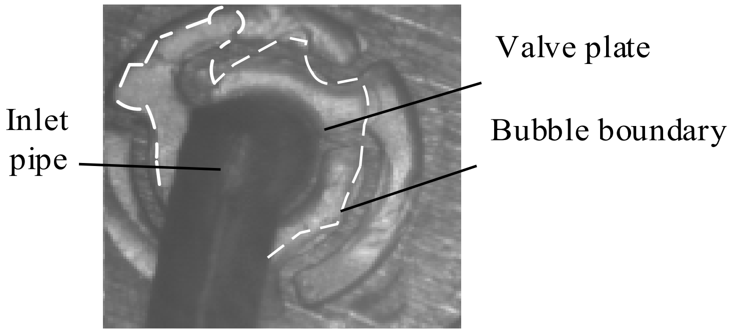


Figure 2. Bubble stayed around inlet valve.

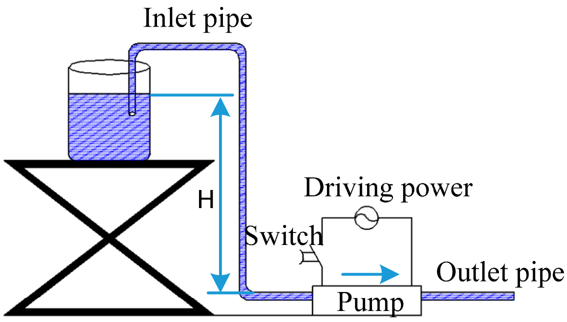


Figure 3. Air block under positive pressure.

3. Valve Structure and Bubble Flow

3.1. The Pressure Drop from Bubble Flow in the Valve

As shown in Figure 4, when the pump works, the check valve vibrates periodically, the maximum distance between valve plate and the base is called valve opening height, shown with H_v. The valve plate thickness used in the paper is 100–300 μm, which is in accordance with micro-channel definition. As the bubbles moves in the micro-channel, the pressure drop occurs, and the pressure drop is directly related with the section of the micro-channel [17–20]. The micro-channel between inlet/outlet and the valves, the valve opening height H_v influence the micro-channel section size dynamically, which also influence the bubble flow resistance. When the valve plate opens, the bubble gets through between valve plate and the base into the pump chamber, as shown in Figure 4. Based on the micro-pump working principle, there are two phases, sucking phase and discharging phase. During sucking phase, inlet valve opens, outlet valve closes. In discharging phase, inlet valve and outlet valve do the opposite compared with sucking phase. Therefore, during the two phases, there are pressure drops ΔP_{BO} and ΔP_{BI} separately produced when the bubble goes through inlet valve and outlet valve, and they are individual. Meanwhile, since the structures of inlet valve and outlet valve are the same, the pressure drop produced in sucking phase is also produced in discharging phase. In this paper, the inlet valve in sucking process is selected for analysis.

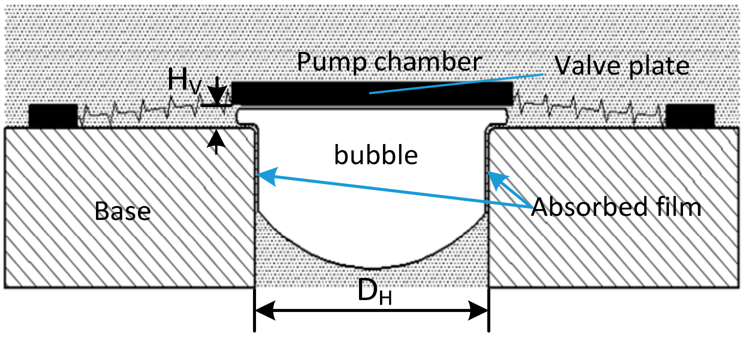


Figure 4. Bubble through valve plate.

The valve opening height H_v in this paper is 100–300 μm, as the bubble gets through, taking the valve as a rectangular section pipe with the width H_v and length πD_H which is inlet pipe circumference. Wong *et al.* [17] show that in a polygonal capillary, a long bubble acts as a leaky piston, the liquid can either push the bubble (plug flow) or bypass the bubble through corner channels (corner flow). When the bubble goes through the valve opening gap, as is shown in Figure 4, since there is no corner area, when the bubble goes through the gap, there is only plug flow. Wong points out the plug flow obeys the pressure-velocity relation of the bubble because the pressure driving the plug flow is dissipated predominantly by the liquid films lubricating the bubble, as in circular capillaries. Suppose the bubble disperses in the radial direction homogeneously, based on [20], the pressure drop occurs when the bubble goes through inlet valve opening gap is:

$$\Delta P_{BI} = 7.16\left(3\frac{\mu_L u_B}{\sigma}\right)^{\frac{2}{3}}\left(\frac{\sigma}{d}\right) \tag{1}$$

where μ_L is dynamic viscosity of water, u_B is mean velocity of bubble, σ is surface tension, d is the equivalent diameter of the capillary, then:

$$d = H_v \tag{2}$$

The valve opening height = 100~300 μm. Under 25 °C, $\mu_L = 0.00089\,\mathrm{N}\cdot\mathrm{s/m^2}$, $\sigma = 0.0072\,N/\mathrm{m}$ [21], then Equation (1) is changed to:

$$\Delta P_{BI} = 0.05733\,(u_B)^{\frac{2}{3}}/H_v \tag{3}$$

Supposing the bubble has the same speed with the liquid, and the outflow of the pump is stable, when the outflow of the pump keeps the same, if the valve opening height increases, u_B will decreases, the pressure drop ΔP_{BI} will decrease.

$$\Delta P \approx \Delta P_{BI} \text{ or } \Delta P \approx \Delta P_{BO} \tag{4}$$

ΔP is the driving pressure, the channel is easily blocked by the bubble. Based on Equation (3) and [20], when the valve opening height increases, the pressure drop ΔP_{BI} from the bubble will decrease, then it's easy for the bubble to get through, which can reduce the air block probability in the pump. Therefore, the valve opening height is a main factor in air block, changing the valve opening height through optimizing the valve structure is able to reduce air block probability.

3.2. Valve Opening Height and Equivalent Stiffness

The valve opening height [22]:

$$H_v = \frac{\Delta P_v A_v}{k_v} \tag{5}$$

where k_v is the valve equivalent stiffness, ΔP_v is the pressure drop between the two sides of the valve, A_v is the valve effective cross section area. From Equation (5) when the pressure drop keeps the same, the smaller k_v, the bigger the valve opening height .The valve structure is shown in Figure 5a in the paper, the valve is modeled as a cantilever beam, as shown in Figure 5b, the equivalent stiffness [22]:

$$k_v = \frac{bt^3 E}{4nl^3} \tag{6}$$

where E is the elastic modulus of the material, l is the length of the beam, n is the number of the beam, b is the width, t is the thickness. When the cantilever beam structure of the valve stays the same, E is 128 GPa, n is 3, l is 13.00 mm, b is 2.50 mm, $A_v = \pi \times \left(\frac{D_H}{2}\right)^2 = 0.79\ \text{mm}^2$, take Equation (6) into Equation (5):

$$H_v = \frac{4\Delta P_v A_v n l^3}{bt^3 E} = (6.47 \times 10^{-20})\frac{\Delta P_v}{t^3} \tag{7}$$

From Equation (7), the cube of the thickness t is inversely proportional to the opening height H_v, when the valve thickness t reduces, the valve opening height H_v will increase.

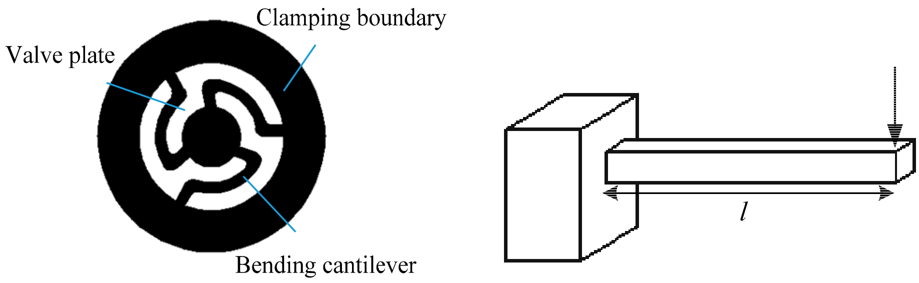


Figure 5. Valve bending cantilever beam. (**a**) Structure; (**b**) Simplified force analysis.

3.3. The Valve Opening Height and Diameter Ratio

To ensure the sealing performance, the valve plate diameter D_v must be bigger than the base hole diameter D_h. When the medium is pure air, the diameter ratio R_D slightly influences the valve opening height H_v, where $R_D = \frac{D_v}{D_h}$. When the medium is pure liquid, since the valve plate is bigger than the base hole, there is gap existing between the area of the valve plate in contact with the base and the base itself, and there is big flow resistance in the gap area, the diameter ratio R_D has big influence on the valve opening height H_v [22]. When the medium is the mixture of air and liquid, the diameter ratio R_D mainly influences the valve opening height H_v by capillarity, as shown in Figure 6, supposing there are bubbles in both sides of the valve plate, and there is liquid membrane in the gap between the valve plate and the base, then the opening condition of the valve is

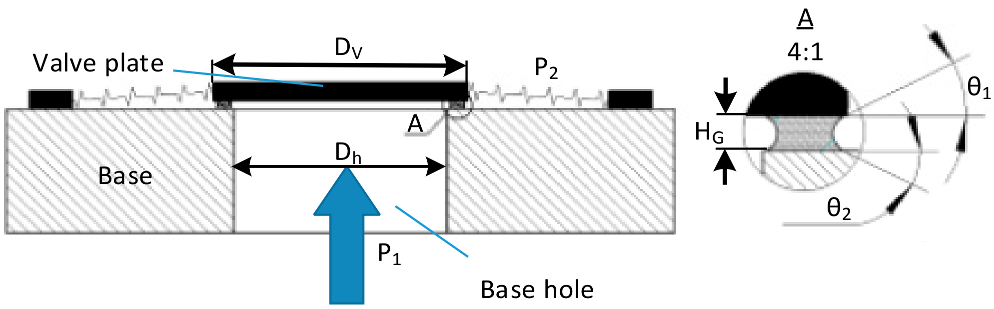


Figure 6. Opening and force for the inlet valve.

$$\pi\frac{D_h^2}{4}(P_1 - P_2) \geqslant \pi\left(\frac{D_v^2}{4} - \frac{D_h^2}{4}\right)P_2 + F_L \tag{8}$$

where D_v is the valve plate diameter, D_h is the base hole diameter, P_1 is the inlet pressure, P_2 is the pressure in the pump channel, F_L is the capillary force between the valve plate and the base. The capillary force [23]:

$$F_L = \frac{\pi\left(D_v^2 - D_h^2\right)\gamma_L\left(\cos\theta_1 - \cos\theta_2\right)}{4H_G} \tag{9}$$

where θ_1 and θ_2 are the contact angel between the liquid and the lower side of the valve plate and upper side of the base, H_G is the gap height between the valve plate and the base, γ_L liquid surface tension. Combining Equations (8) and (9), the valve plate opening condition is

$$(P_1 - P_2) \geqslant \left((\frac{D_v}{D_h})^2 - 1\right)\left[P_2 + \frac{\gamma_L\left(\cos\theta_1 - \cos\theta_2\right)}{H_G}\right] \tag{10}$$

When the assembly process is consistent, H_G keeps the same, when the materials of the valve plate and the base keep no change, the liquid keeps the same, there is no change in γ_L, θ_1, θ_2, from [23], as inorganic salt and alkali are added into the water, the γ_L of the water increases as the solute concentration increases, as the organic acid and alcohol are added into the water, the γ_L of the water decreases as the solute concentration increases. Because of the limitation of the paper length, the surface tensions of different working media are not measured and investigated, but only the pure water. When the pressures in both sides of the valve plate P_1, P_2 keep the same, Equation (10) can be simplified as:

$$\Delta P_v \geqslant A \times \left(R_D^2 - 1\right) \tag{11}$$

ΔP_v is the pressure difference from the micro-pump, A is constant, R_D is diameter ratio. From Equation (11), the smaller the diameter ratio R_D is, the easier the valve plate can open, the valve opening height H_v will increase.

4. Experiment and Discussion

From the theoretical analysis in Section 3, reducing the valve equivalent stiffness, or the diameter ratio can both increase the valve opening height to decrease the micro-pump air block resistance. To validate the theoretical analysis, the valves with different thicknesses t and diameters D_v are made to change the valve equivalent stiffness and diameter ratio. Laser micrometer is used to measure the valve opening height H_v, meanwhile, the air block probability is compared. The parameters of the micro-pump are shown in Table 1.

Table 1. The parameter of the micro-pump.

Type	Value and Material
Pump size	27 mm × 27 mm × 7 mm
Pump Material	PMMA (Polymethylmethacrylate)
Base plate outer diameter of the vibrator	Φ20 mm
Base plate thickness of the vibrator	0.2 mm
Base hole diameter D_h	Φ1 mm
Valve diameter D_v	Φ1.2, Φ1.4, Φ 1.6, Φ1.8, Φ2.0 mm
The connecting pipe material	rubber
The connecting pipe diameter	Φ4 mm (outer), Φ2 mm (inner)
Check valve structure	wheel type
Check valve Material	beryllium bronze
Check valve Thickness t	20, 30, 40, 50, 60 μm
Power	110 V, 50 Hz, square wave

To obtain bubbles precisely, manually adding bubble device is made, as shown in Figures 7 and 8 with PLC (Programmable Logical Controller), the device can control the step motor to run according to a certain angel, which can push the inlet pipe to pull in and out of the liquid periodically, the bubbles can get into the pump regularly. To control the volume of the bubbles, the time staying in the air for the inlet pipe is set up. The partial enlarged drawing in Figure 8 is the graduated scale printed in the inlet pipe to measure the bubble volume.

When the device starts working, after the first bubble is excluded from the outlet pipe, the next bubble is allowed to get into the pump, until the air block occurring, stop inserting a new bubble, under big external pressure in the inlet pipe, the bubble is taken out to eliminate the air block, and fill the channel with liquid again to restart the testing. Record air block times N_{BL} through a certain bubble quantity in the channel. In the experiment, one hundred bubbles are sets up to get into the channel, check the air block average number for five times. Air block probability is defined as $N_{BL}/100$. To make the comparison more effective, three different kinds of bubble volumes are used 0.2, 0.4 and 0.6 mL.

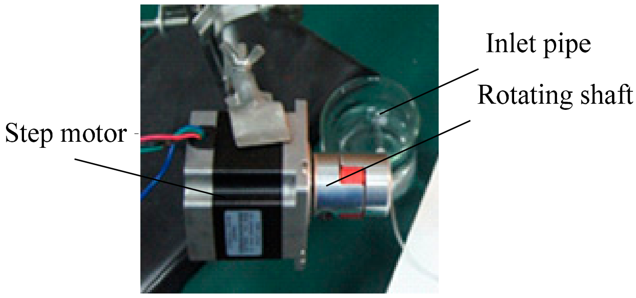


Figure 7. Manually adding bubble device.

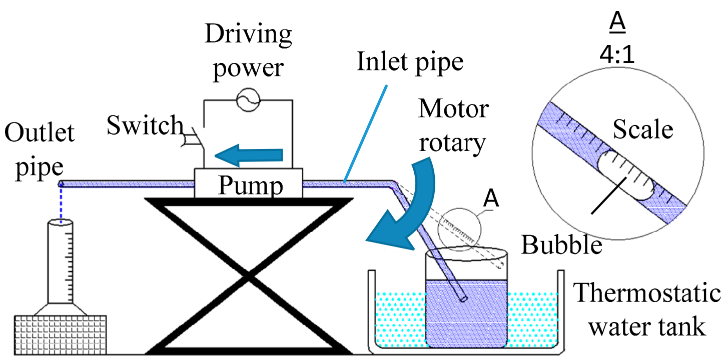


Figure 8. Micro-pump air block experiment device.

Laser with wave length 355 nm is used to manufacture the valve, the valve thickness t = 40 μm. The diameter ratios R_D are 1.2, 1.4, 1.6, 1.8 and 2.0 separately. The valve opening height H_v and air block times N_{BL} in the experiment is shown in Figures 9 and 10.

With the diameter ratio R_D increasing, the valve opening height H_v is reducing gradually, which is consistent with Equation (7). The concept of equivalent stiffness is used in Equation (7) to describe the movement of the valve plate, and ΔP_v is supposed to be the same, therefore, there is a certain deviation between the prediction from Equation (7) and the real condition shown in Figure 10, but from Figure 10, we can see Equation (7) can still show the relationship well between H_v and t. Also, in the samples, increase the bubble volume, the occurrence of air block is more frequent. In this experiment, diameter ratio R_D = 1.2 is selected as the most optimized one, since diameter ratio R_D

which is below 1.2 makes the assembly of the valve very difficult, and the sealing effect is also not ensured, which makes bad influence to the pump performance, so diameter ratio R_D below 1.2 is not selected in the experiment.

As R_D = 1.2, testing on valves with different thickness t = 20, 30, 40, 50 and 60 µm were carried out. The results are shown in Figures 11 and 12.

From Figures 11 and 12 with the thickness reduction of the valve plate, the valve opening height H_v increases, and air block times N_{BL} reduces, which is in accordance with Section 3. Within the samples, the most optimized valve thickness is 20 µm. The thickness t below 20 µm is not selected in the experiment, because too small thickness can reduce the micro-pump best working frequency dramatically, and more sensitive to the frequency, and furthermore, influence the comparison.

In the experiment, the best combination for the valve: diameter ratio is 1.2, thickness is 20 µm. With this combination for the micro-pump prototype, the measured valve opening height is 252 µm, and when the bubble volumes are 0.2, 0.4 and 0.6 mL, the air block probability are 0%, 1% and 2%.

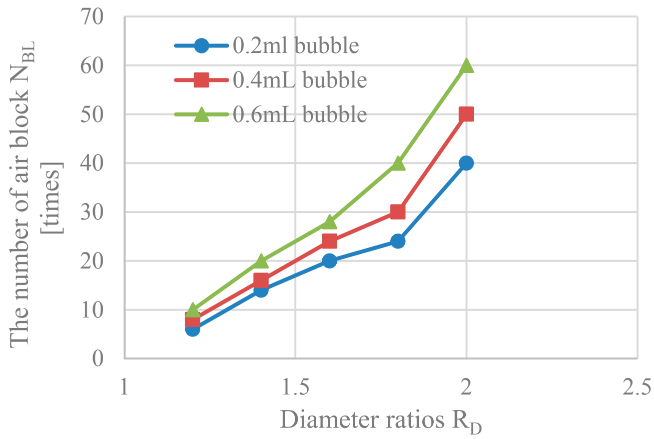


Figure 9. The relationship between diameter ratio R_D and air block times N_{BL}, when Thickness of the check valve t = 40 µm.

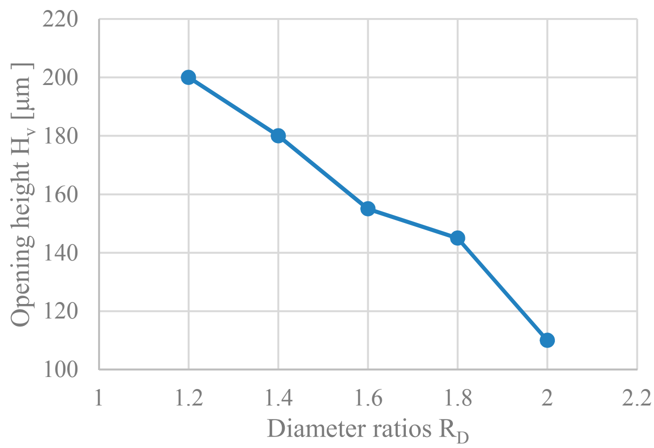


Figure 10. The relationship between diameter ratio R_D and the valve opening height H_v, when Thickness of the check valve t = 40 µm.

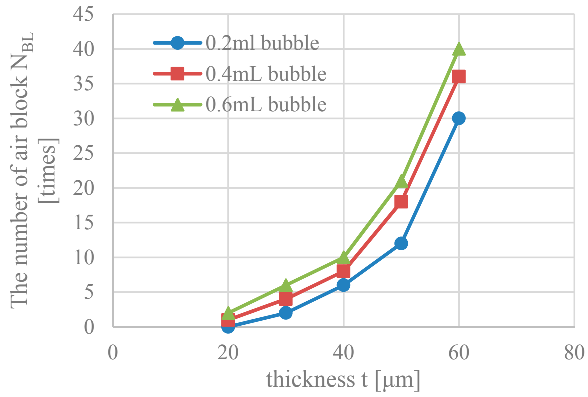


Figure 11. The relationship between thickness t and air block times N_{BL}, when R_D = 1.2.

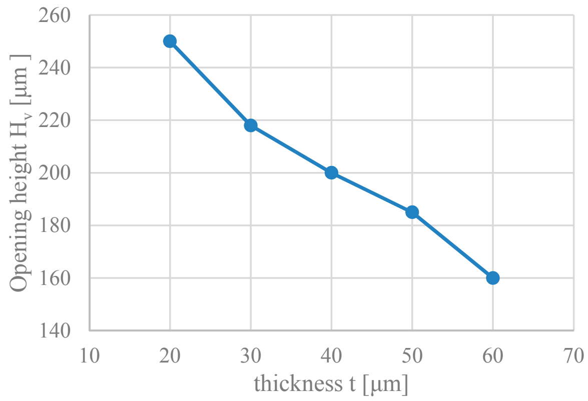


Figure 12. The relationship between thickness t and valve opening height H_v, when R_D = 1.2.

5. Conclusions

- Air block is caused by the combination of bubble, liquid and check valve.
- When the valve diameter ratios R_D are 1.2, 1.4, 1.6, 1.8 and 2.0, measure the valve opening height and air block probability. The experiment results show that when the diameter ratio R_D = 1.2, the air block probability is the lowest.
- When the valve thicknesses are 20, 30, 40, 50 and 60 μm, measure the valve opening height and air block probability. The experiment result shows that when the thickness t = 20 μm, the air block probability is the lowest.
- Within the samples, the best combination of the valve is when the diameter ratio R_D = 1.2 and thickness t = 20 μm. Under this combination, the valve opening height H_v is 252 μm, and within the given bubble volumes, the air block probability is below 2%.

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Conflicts of Interest: The authors declare no conflict of interest.

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