Electronic supplementary information For

Analyzing water-head-driven microfluidic oscillators for autonomous control of period and flow rate

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I. Open condition of the valve and its threshold pressure

The open condition of valve m is $P_{VTm} - P_{VBm} > P_{OTHm}$. Because $P_{VTm} = P_I$ and $P_{VBm} = P_{CBn}$, the open condition is rewritten as $P_{CBn} < P_I - P_{OTHm}$. We measured the open threshold pressure of valve m (m = 1, 2) with the oscillator. To obtain P_{OTm}, we measured P_{VTm}, P_{VBm}, and P_{CTm} of the oscillator with pressure sensors (PX309-015G5V, Omega Eng). We maintained P_{VTm} at 3.7 kPa and decreased P_{VBm}. At the moment valve m opened, P_{CTm} rose rapidly (Fig. S1a).

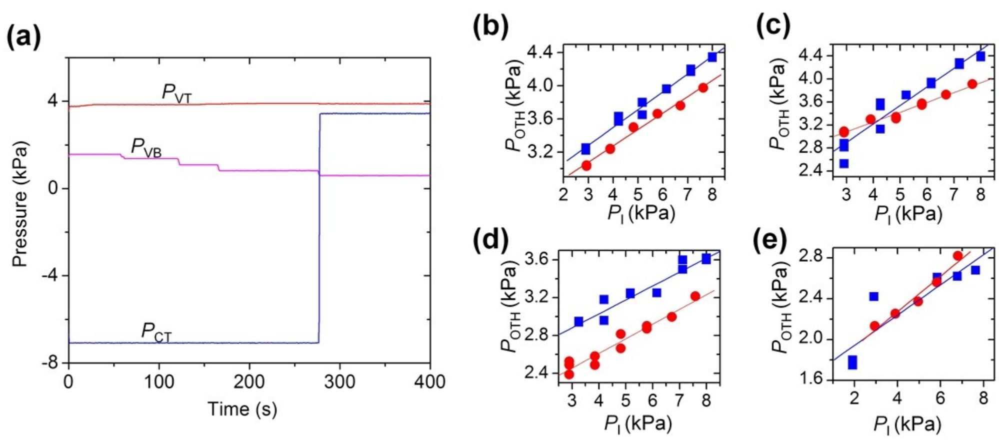

Fig. S1. Measurement of open threshold pressure. (a) Pressure profiles of P_{VB} and P_{CT}. (b to e) Calibration curves of P_{OTHn} with respect to P_I. R_F is 3.2×10^{11}, 1.2×10^{12}, 2.5×10^{13}, and 1.3×10^{15} N s m^{-5} from (b) to (e), respectively. The blue and red lines correspond to valves 1 and 2, respectively.

At this time, we obtained P_{OTHm} from $P_{OTm} = P_{VTm} - P_{VBm}$. Figures S1b to S1e show the calibration curves of P_{OTHm} with respect to P_{VTm} (=P_I) under different R_F. From the curves of Figs. S1b to S1e, we obtained $P_{OTH1} = -341.37 \log_{10}(R_F) + 7428.40$ and $P_{OTH2} = -298.02 \log_{10}(R_F) + 6683.15$ at P_I =3.7 kPa, and applied them to Figs. 4 and 5 in the main text. The unit of P_{OTH1} and P_{OTH2} is Pa.

II. Theoretical derivation of equations for P_{CBn} and P_{CTn}

One oscillation period includes the sequential open-process of the two valves. At the k^{th} oscillation period (k = 0, 1, 2…), valve 1 opens for $t_{I1}^{(k)} \le t \le t_{F1}^{(k)}$ and then valve 2 opens for $t_{I2}^{(k)} \le t \le t_{F2}^{(k)}$. Figre S2 shows the pressure profiles of P_{CT1}, P_{CB1}, and P_{CB2} at the k^{th} period. To derive equations, we used the circuit diagram that depicts the fluidic connection at the state when valve 1 is open and valve 2 is closed (Fig. S3).

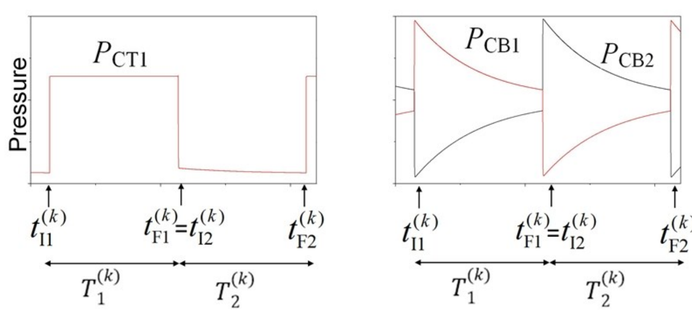

Fig. S2. Pressure profiles of P_{CT1}, P_{CB1}, and P_{CB2} at the k^{th} oscillation period.

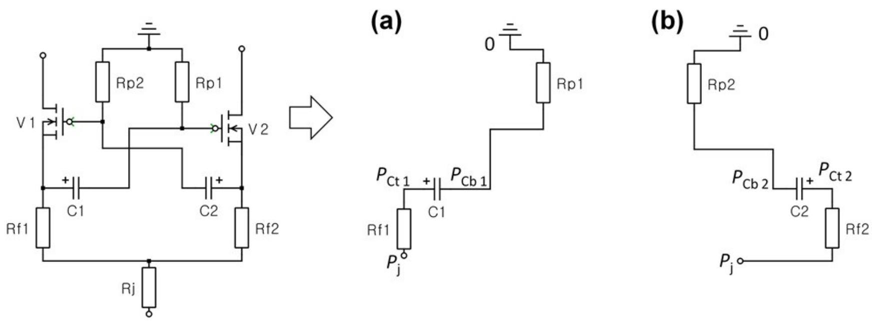

Fig. S3. For the state when valve 1 is open, the relation between P_{CT1} and P_{CB1} is obtained in (a) and the relation between P_{CT2} and P_{CB2} is obtained in (b).

While valve 1 is open,

$$P_{\mathrm{CT1}} = P_{\mathrm{I}}. \tag{S1}$$

From Fig. S3a, we obtain

$$C_1 \frac{d}{dt}(P_{\mathrm{CT1}} - P_{\mathrm{CB1}}) = \frac{P_{\mathrm{CB1}} - 0}{R_{\mathrm{P1}}}. \tag{S2}$$

By the initial condition of P_{CB1} at $t_{\mathrm{I1}}^{(k)}$, $P_{\mathrm{CB1}}(t)$ is

$$P_{\mathrm{CB1}}(t) = P_{\mathrm{CB1}}(t_{\mathrm{I1}}^{(k)}) e^{-\frac{t - t_{\mathrm{I1}}^{(k)}}{C_1 R_{\mathrm{P1}}}}. \tag{S3}$$

From Fig. S3b, we obtain

$$\frac{0 - P_{\mathrm{CB2}}}{R_{\mathrm{P2}}} = C_2 \frac{d}{dt}(P_{\mathrm{CB2}} - P_{\mathrm{CT2}}) = \frac{P_{\mathrm{CT2}} - P_{\mathrm{J}}}{R_{\mathrm{F2}}}. \tag{S4}$$

After removing P_{CT2} in eqn (S4),

$$-(\frac{R_{\mathrm{F2}}}{R_{\mathrm{P2}}} + 1) \frac{d}{dt} P_{\mathrm{CB2}} = \frac{1}{C_2 R_{\mathrm{P2}}} P_{\mathrm{CB2}}. \tag{S5}$$

By the initial condition of P_{CB2} at $t_{\mathrm{I1}}^{(k)}$, eqn (S5) is

$$P_{\mathrm{CB2}}(t) = P_{\mathrm{CB2}}(t_{\mathrm{I1}}^{(k)}) e^{-\frac{t - t_{\mathrm{I1}}^{(k)}}{C_2 (R_{\mathrm{F2}} + R_{\mathrm{P2}})}}. \tag{S6}$$

Then from eqn (S4),

$$P_{\mathrm{CT2}}(t) = P_{\mathrm{J}} - \frac{R_{\mathrm{F2}}}{R_{\mathrm{P2}}} P_{\mathrm{CB2}}(t) \,. \tag{S7}$$

The equations for the open state of valve 2 can be derived in the same manner. Table S1 summarizes equations for the changes of pressures and duration times of each valve's openings.

Table S1. Equations at the open state of each valve.

Valve 1 open state: $t_{\mathrm{i1}}^{(k)} \le t \le t_{\mathrm{f1}}^{(k)}$	Valve 2 open state: $t_{\mathrm{i2}}^{(k)} \le t \le t_{\mathrm{f2}}^{(k)}$
$P_{\mathrm{CT1}} = P_{\mathrm{I}}$ (S1)	$P_{\mathrm{CT2}} = P_{\mathrm{I}}$ (S8)
$P_{\mathrm{CB1}}(t) = P_{\mathrm{CB1}}(t_{\mathrm{I1}}^{(k)}) e^{-\frac{t - t_{\mathrm{I1}}^{(k)}}{C_1 R_{\mathrm{P1}}}}$ (S3)	$P_{\mathrm{CB2}}(t) = P_{\mathrm{CB2}}(t_{\mathrm{I2}}^{(k)}) e^{-\frac{t - t_{\mathrm{I2}}^{(k)}}{C_2 R_{\mathrm{P2}}}}$ (S9)
$P_{\mathrm{CB2}}(t) = P_{\mathrm{CB2}}(t_{\mathrm{I1}}^{(k)}) e^{-\frac{t - t_{\mathrm{I1}}^{(k)}}{C_2 (R_{\mathrm{F2}} + R_{\mathrm{P2}})}}$ (S6)	$P_{\mathrm{CB1}}(t) = P_{\mathrm{CB1}}(t_{\mathrm{I2}}^{(k)}) e^{-\frac{t - t_{\mathrm{I2}}^{(k)}}{C_1 (R_{\mathrm{F1}} + R_{\mathrm{P1}})}}$ (S10)
$P_{\mathrm{CT2}}(t) = P_{\mathrm{J}} - \frac{R_{\mathrm{F2}}}{R_{\mathrm{P2}}} P_{\mathrm{CB2}}(t)$ (S7)	$P_{\mathrm{CT1}}(t) = P_{\mathrm{J}} - \frac{R_{\mathrm{F1}}}{R_{\mathrm{P1}}} P_{\mathrm{CB1}}(t)$ (S11)

III. Theoretical derivation of equations of $P_{\mathrm{CB}n}$ at times $t_{\mathrm{I}n}^{(k)}$ and $t_{\mathrm{F}n}^{(k)}$

We derive equations for $P_{\mathrm{CB1}}(t_{\mathrm{I2}}^{(k)})$, $P_{\mathrm{CB1}}(t_{\mathrm{F1}}^{(k)})$, $P_{\mathrm{CB2}}(t_{\mathrm{I1}}^{(k)})$, and $P_{\mathrm{CB2}}(t_{\mathrm{F2}}^{(k)})$. The open condition of valve 2 is $P_{\mathrm{VT2}} - P_{\mathrm{VB2}} > P_{\mathrm{OTH2}}$. At the moment valve 2 is opened in the k^{th} period, the condition is

$$P_{\mathrm{VT2}}(t_{\mathrm{F1}}^{(k)}) - P_{\mathrm{VB2}}(t_{\mathrm{F1}}^{(k)}) = P_{\mathrm{OTH2}} \,,$$

with

$$P_{\mathrm{VT2}}(t_{\mathrm{F1}}^{(k)}) = P_{\mathrm{I}} \text{ and } P_{\mathrm{VB2}}(t_{\mathrm{F1}}^{(k)}) = P_{\mathrm{CB1}}(t_{\mathrm{F1}}^{(k)}) \,. \tag{S12}$$

Thus,

$$P_{\mathrm{CB1}}(t_{\mathrm{F1}}^{(k)}) = P_{\mathrm{I}} - P_{\mathrm{OTH2}} \,. \tag{S13}$$

From the continuity of pressure differences across capacitor 1,

$$P_{\mathrm{CT1}}(t_{\mathrm{F1}}^{(k)}) - P_{\mathrm{CB1}}(t_{\mathrm{F1}}^{(k)}) = P_{\mathrm{CT1}}(t_{\mathrm{I2}}^{(k)}) - P_{\mathrm{CB1}}(t_{\mathrm{I2}}^{(k)})\,. \tag{S14}$$

From Eqs. (S1) and (S13), eqn (S14) is

$$P_{\mathrm{CT1}}(t_{\mathrm{I2}}^{(k)}) - P_{\mathrm{CB1}}(t_{\mathrm{I2}}^{(k)}) = P_{\mathrm{OTH2}}\,. \tag{S15}$$

When valve 2 opens, valve 1 is closed. From Fig. S2(a), we obtain:

$$\frac{0 - P_{\mathrm{CB1}}(t_{\mathrm{I2}}^{(k)})}{R_{\mathrm{P1}}} = \frac{P_{\mathrm{CT1}}(t_{\mathrm{I2}}^{(k)}) - P_{\mathrm{J}}}{R_{\mathrm{F1}}}\,. \tag{S16}$$

From Eqs. (S15) and (S16), we derive an equation for P_{CB1} at the moment valve 2 opens:

$$P_{\mathrm{CB1}}(t_{\mathrm{I2}}^{(k)}) = \frac{R_{\mathrm{P1}}}{R_{\mathrm{F1}} + R_{\mathrm{P1}}}(P_{\mathrm{J}} - P_{\mathrm{OTH2}})\,. \tag{S17}$$

Similarly, at the moment valve 1 opens in the k^{th} period, the condition of valve 1 is

$$P_{\mathrm{CB2}}(t_{\mathrm{F2}}^{(k)}) = P_{\mathrm{I}} - P_{\mathrm{OTH1}}\,. \tag{S18}$$

From the continuity of pressure differences across capacitor 2,

$$P_{\mathrm{CB2}}(t_{\mathrm{I1}}^{(k)}) = \frac{R_{\mathrm{P2}}}{R_{\mathrm{F2}} + R_{\mathrm{P2}}}(P_{\mathrm{J}} - P_{\mathrm{OTH1}})\,. \tag{S19}$$

Table S2 summarizes the equations of $P_{\mathrm{CB}n}$ at times $t_{\mathrm{I}n}^{(k)}$ and $t_{\mathrm{F}n}^{(k)}$.

Table S2. Equations of $P_{\mathrm{CB}n}$ at times $t_{\mathrm{I}n}^{(k)}$ and $t_{\mathrm{F}n}^{(k)}$.

P_{CB1}	P_{CB2}
$P_{\mathrm{CB1}}(t_{\mathrm{F1}}^{(k)}) = P_{\mathrm{I}} - P_{\mathrm{OTH2}}$ (S13)	$P_{\mathrm{CB2}}(t_{\mathrm{F2}}^{(k)}) = P_{\mathrm{I}} - P_{\mathrm{OTH1}}$ (S18)
$P_{\mathrm{CB1}}(t_{\mathrm{I2}}^{(k)}) = \dfrac{R_{\mathrm{P1}}}{R_{\mathrm{F1}} + R_{\mathrm{P1}}}(P_{\mathrm{J}} - P_{\mathrm{OTH2}})$ (S17)	$P_{\mathrm{CB2}}(t_{\mathrm{I1}}^{(k)}) = \dfrac{R_{\mathrm{P2}}}{R_{\mathrm{F2}} + R_{\mathrm{P2}}}(P_{\mathrm{J}} - P_{\mathrm{OTH1}})$ (S19)

IV. Theoretical derivation of equations for fluidic switching periods

From eqn (S3), we obtain the duration time of the opening of valve 1:

$$T_1^{(k)} = t_{\mathrm{F1}}^{(k)} - t_{\mathrm{I1}}^{(k)} = C_1 R_{\mathrm{P1}} \ln\left[\frac{P_{\mathrm{CB1}}(t_{\mathrm{I1}}^{(k)})}{P_{\mathrm{CB1}}(t_{\mathrm{F1}}^{(k)})}\right]. \tag{S20}$$

Similarly, the duration time of the opening of valve 2 can be written as

$$T_2^{(k)} = t_{\mathrm{F2}}^{(k)} - t_{\mathrm{I2}}^{(k)} = C_2 R_{\mathrm{P2}} \ln\left[\frac{P_{\mathrm{CB2}}(t_{\mathrm{I2}}^{(k)})}{P_{\mathrm{CB2}}(t_{\mathrm{F2}}^{(k)})}\right]. \tag{S21}$$

The k^{th} switching period of the two valves is $T^{(k)} = T_1^{(k)} + T_2^{(k)}$. Equations (S20) and (S21) show that $T^{(k)}$ includes $P_{\mathrm{CB1}}(t_{\mathrm{I1}}^{(k)})$, $P_{\mathrm{CB1}}(t_{\mathrm{F1}}^{(k)})$, $P_{\mathrm{CB2}}(t_{\mathrm{I2}}^{(k)})$, and $P_{\mathrm{CB2}}(t_{\mathrm{F2}}^{(k)})$. Because we obtained $P_{\mathrm{CB1}}(t_{\mathrm{F1}}^{(k)})$ and $P_{\mathrm{CB2}}(t_{\mathrm{F2}}^{(k)})$ (Table S2), we need $P_{\mathrm{CB1}}(t_{\mathrm{I1}}^{(k)})$ and $P_{\mathrm{CB2}}(t_{\mathrm{I2}}^{(k)})$ for $T^{(k)}$.

At $k = 0$, we assume valve 1 opens and valve 2 closes. Thus,

$$P_{\mathrm{CB1}}(t_{\mathrm{I1}}^{(0)}) = P_{\mathrm{CT1}}(t_{\mathrm{I1}}^{(0)}) = P_{\mathrm{I}}. \tag{S22}$$

From eqn (S4),

$$P_{\mathrm{CB2}}(t_{\mathrm{I1}}^{(0)}) = P_{\mathrm{CT2}}(t_{\mathrm{I1}}^{(0)}) = \frac{R_{\mathrm{P2}}}{R_{\mathrm{F2}} + R_{\mathrm{P2}}} P_{\mathrm{J}}. \tag{S23}$$

From Eqs. (S13), (S20), and (S22), the duration time of valve 1 at the 0^{th} period is

$$T_1^{(0)} = t_{\mathrm{F1}}^{(0)} - t_{\mathrm{I1}}^{(0)} = C_1 R_{\mathrm{P1}} \ln\left[\frac{P_{\mathrm{I}}}{P_{\mathrm{I}} - P_{\mathrm{OTH2}}}\right]. \tag{S24}$$

When valve 2 opens, the continuity of pressure differences across capacitor 2 should be met:

$$P_{\mathrm{CT2}}(t_{\mathrm{F1}}^{(0)}) - P_{\mathrm{CB2}}(t_{\mathrm{F1}}^{(0)}) = P_{\mathrm{CT2}}(t_{\mathrm{I2}}^{(0)}) - P_{\mathrm{CB2}}(t_{\mathrm{I2}}^{(0)})\,. \tag{S25}$$

Applying Eqs. (S6)–(S8), and (S24) to eqn (S25), we obtain P_{CB1} at the moment valve 2 opens in the 0$^{\mathrm{th}}$ period:

$$P_{\mathrm{CB2}}(t_{\mathrm{I2}}^{(0)}) = P_{\mathrm{I}} - P_{\mathrm{J}} + P_{\mathrm{J}}\left(\frac{P_{\mathrm{I}} - P_{\mathrm{OTH2}}}{P_{\mathrm{I}}}\right)^{a_1}, \tag{S26}$$

with

$$a_1 = \frac{C_1 R_{\mathrm{P1}}}{C_2 (R_{\mathrm{F2}} + R_{\mathrm{P2}})}\,. \tag{S27}$$

At $k \geq 1$, we can obtain $P_{\mathrm{CB1}}(t_{\mathrm{I1}}^{(k)})$ and $P_{\mathrm{CB2}}(t_{\mathrm{I2}}^{(k)})$.

At the moment valve 1 opens in the k^{th} period, the continuity condition of pressure difference across capacitor 1 is

$$P_{\mathrm{CT1}}(t_{\mathrm{F2}}^{(k-1)}) - P_{\mathrm{CB1}}(t_{\mathrm{F2}}^{(k-1)}) = P_{\mathrm{CT1}}(t_{\mathrm{I1}}^{(k)}) - P_{\mathrm{CB1}}(t_{\mathrm{I1}}^{(k)})\,. \tag{S28}$$

From eqn (S10) and (S17),

$$P_{\mathrm{CB1}}(t_{\mathrm{F2}}^{(k-1)}) = \frac{R_{\mathrm{P1}}}{R_{\mathrm{F1}} + R_{\mathrm{P1}}}(P_{\mathrm{J}} - P_{\mathrm{OTH2}})e^{-\frac{t_{\mathrm{F2}}^{(k-1)} - t_{\mathrm{I2}}^{(k-1)}}{C_1 (R_{\mathrm{F1}} + R_{\mathrm{P1}})}}\,. \tag{S29}$$

From eqns (S18) and (S21), eqn (S29) is

$$P_{\mathrm{CB1}}(t_{\mathrm{F2}}^{(k-1)}) = \frac{R_{\mathrm{P1}}}{R_{\mathrm{F1}} + R_{\mathrm{P1}}}(P_{\mathrm{J}} - P_{\mathrm{OTH2}})\left(\frac{P_{\mathrm{I}} - P_{\mathrm{OTH1}}}{P_{\mathrm{CB2}}(t_{\mathrm{I2}}^{(k-1)})}\right)^{a_2} \tag{S30}$$

with

$$a_2 = \frac{C_2 R_{\mathrm{P2}}}{C_1 (R_{\mathrm{F1}} + R_{\mathrm{P1}})}\,. \tag{S31}$$

From eqn (S11),

$$P_{\mathrm{CT1}}(t_{\mathrm{F2}}^{(k-1)}) - P_{\mathrm{CB1}}(t_{\mathrm{F2}}^{(k-1)}) = P_{\mathrm{J}} - \left(\frac{R_{\mathrm{F1}}}{R_{\mathrm{P1}}} + 1\right) P_{\mathrm{CB1}}(t_{\mathrm{F2}}^{(k-1)}) . \tag{S32}$$

Applying eqns. (S1), (S30), and (S31) to eqn (S28), we obtain:

$$P_{\mathrm{CB1}}(t_{\mathrm{I1}}^{(k)}) = P_{\mathrm{I}} - P_{\mathrm{J}} + (P_{\mathrm{J}} - P_{\mathrm{OTH2}}) \left(\frac{P_{\mathrm{I}} - P_{\mathrm{OTH1}}}{P_{\mathrm{CB2}}(t_{\mathrm{I2}}^{(k-1)})}\right)^{a_2} . \tag{S33}$$

Similarly, we can get

$$P_{\mathrm{CB2}}(t_{\mathrm{I2}}^{(k)}) = P_{\mathrm{I}} - P_{\mathrm{J}} + (P_{\mathrm{J}} - P_{\mathrm{OTH1}}) \left(\frac{P_{\mathrm{I}} - P_{\mathrm{OTH2}}}{P_{\mathrm{CB1}}(t_{\mathrm{I1}}^{(k)})}\right)^{a_1} . \tag{S34}$$

We used $C_1 = C_2$, $R_{\mathrm{F1}} = R_{\mathrm{F2}}$, and $R_{\mathrm{P1}} = R_{\mathrm{P2}}$ in the experiment, and $T^{(k)} = T_1^{(k)} + T_2^{(k)}$. Thus, the final equations for the period are summarized in Table S3.

Table S3. Theoretical equations for period and related pressures

$$T^{(k)} = CR_{\mathrm{P}} \ln\left[\frac{P_{\mathrm{CB1}}\left(t_{\mathrm{I1}}{}^{(k)}\right) P_{\mathrm{CB2}}\left(t_{\mathrm{I2}}{}^{(k)}\right)}{\left(P_{\mathrm{I}} - P_{\mathrm{OTH1}}\right)\left(P_{\mathrm{I}} - P_{\mathrm{OTH2}}\right)}\right] \qquad \text{(S13, S18, S20, S21)}$$

$$P_{\mathrm{CB1}}(t_{\mathrm{I1}}^{(k)}) = P_{\mathrm{I}} - P_{\mathrm{J}} + (P_{\mathrm{J}} - P_{\mathrm{OTH2}}) \left(\frac{P_{\mathrm{I}} - P_{\mathrm{OTH1}}}{P_{\mathrm{CB2}}(t_{\mathrm{I2}}^{(k-1)})}\right)^{a} \qquad \text{(S33)}$$

$$P_{\mathrm{CB2}}(t_{\mathrm{I2}}^{(k)}) = P_{\mathrm{I}} - P_{\mathrm{J}} + (P_{\mathrm{J}} - P_{\mathrm{OTH1}}) \left(\frac{P_{\mathrm{I}} - P_{\mathrm{OTH2}}}{P_{\mathrm{CB1}}(t_{\mathrm{I1}}^{(k)})}\right)^{a} \qquad \text{(S34)}$$

$$\text{with } a = \frac{1}{1 + R_{\mathrm{F}} / R_{\mathrm{P}}} \qquad \text{(S27, S31)}$$

$$\text{and } P_{\mathrm{CB2}}(t_{\mathrm{I2}}^{(0)}) = P_{\mathrm{I}} - P_{\mathrm{J}} + P_{\mathrm{J}} \left(\frac{P_{\mathrm{I}} - P_{\mathrm{OTH2}}}{P_{\mathrm{I}}}\right)^{a} \qquad \text{(S26)}$$

V. Convergence of $P_{CB1}(t_{I1}^{(k)})$ and $P_{CB2}(t_{I2}^{(k)})$

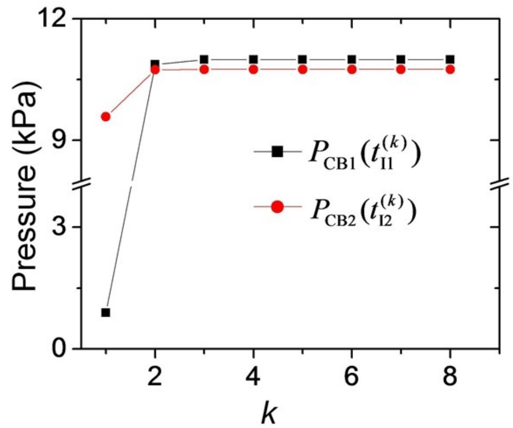

Fig. S4. $P_{CBn}(t_{In}^{(k)})$ converges at k = 3. Here, P_I and P_O are 3.7 and −8.5 kPa, respectively, and R_F and R_P are 1×10^{13} and 5×10^{13} N s m^{-5}, respectively.

VI. Closed threshold pressure

We obtained the closed threshold pressures of valve m (P_{CTHm}) with working oscillators. To obtain P_{CTHm} for Figs. 4 and 5, we used $R_P = 6.1 \times 10^{13}$ N s / m^5 and $P_I = 3.7$ kPa. R_F and P_O are variables. For example, when R_F is 2.4×10^{12} N s / m^5 and P_O was increased from −8.5 to −3.3 kPa, the oscillation stopped at P_O = −3.3 kPa (Figs. S2a and S2b). As P_O increased, $P_{CBn}(t_{In}{}^{(k)})$ decreased and the condition of eqn (4) in the main text was not satisfied at P_O= −3.3 kPa. At such a critical P_O, $P_{CBn}(t_{In}{}^{(k)})$ is equal to $-P_{CTm} + P_I$. This can be rewritten as $P_{CTn} = -P_{CBn}(t_{In}{}^{(k)}) + P_I$. Here, $P_{CBn}(t_{In}{}^{(k)})$ is obtained from eqn (2) in the main text, and k is ≥ 3. As we changed R_F, calibration curves of P_{CTHm} for Figs. 3 and 4 were obtained, as shown in Fig. S5c, where P_{CTH1} = −418.7ln(R_F) + 9372.5 and P_{CTH2}= −416.9ln(R_F) + 9086.6.

To obtain P_{CTHm} for Fig. 5, we used $R_P = 6.1 \times 10^{13}$ and $R_F = 2.4 \times 10^{12}$ N s m^{-5}. P_I and P_O are variables. Figure S5d shows the calibration curves: $P_{CTH1} = 0.3371\ P_O - 1057.9$ and $P_{CTH2} = 0.3412\ P_O - 1261.1$.

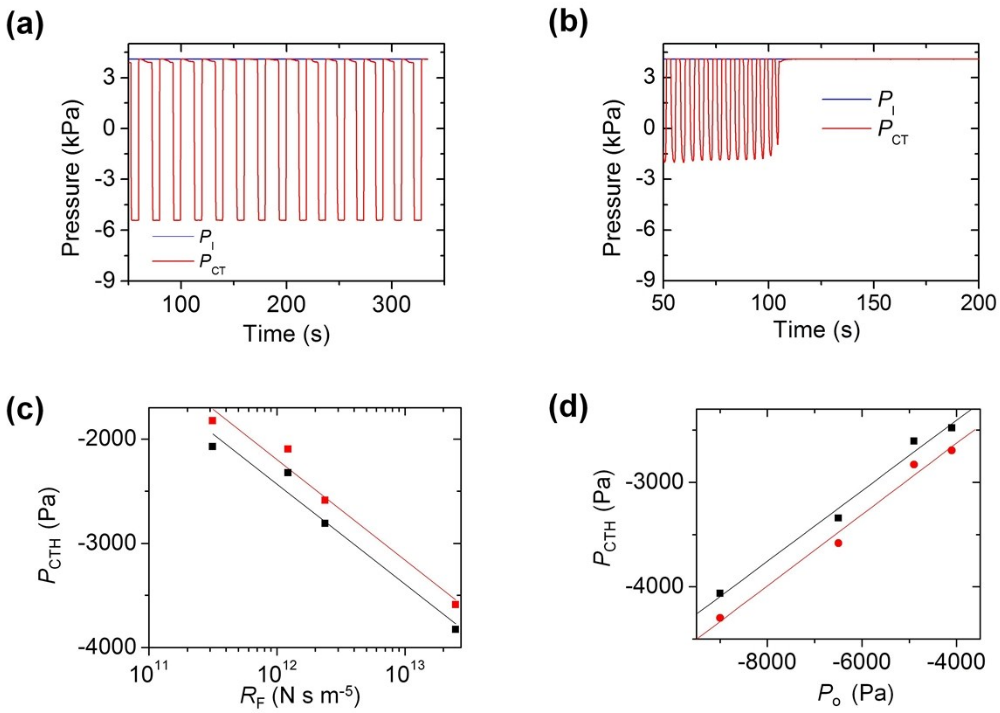

Fig. S5. Measurement of closed threshold pressure. (a and b) Pressure profiles of P_{CTm}. P_O is −8.5 kPa in (a) and −3.3 kPa in (b). (c) Calibration curves of P_{CTHn} with respect to R_F. (d) Calibration curves of P_{CTHm} with respect to P_O. The black and red lines correspond to valves 1 and 2, respectively, in (c) and (d).