Flow Characteristics of Cryogenic Perforated Plate Balanced Flowmeter

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Cryogenic Fluids

Hydrogen transport

Aerospace propellant

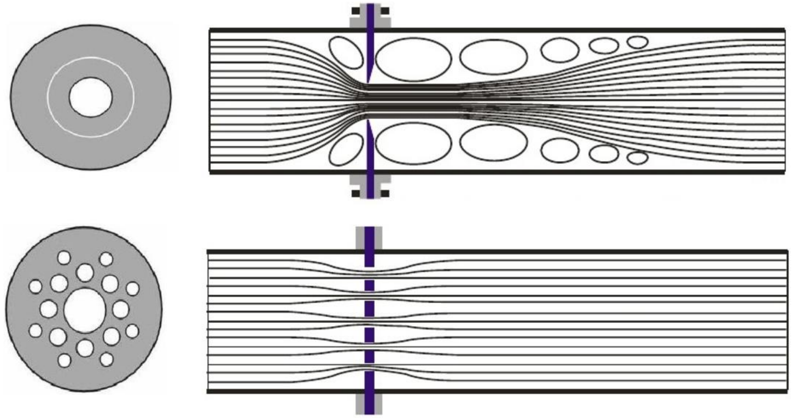
Cold storage medium

LNG terminal

- Flowrate measurement has a more general demand in the production, transport, storage and use of cryogenic fluids.
- Cryogenic fluids are easy to **cavitation**, requiring better performance of the **cryogenic flowmeter**.

Cryogenic Flowmeter

- The standard orifice plate flowmeter is one of the simplest flowmeters, but it is **not suitable** for cryogenic fluids due to its **large pressure loss**.

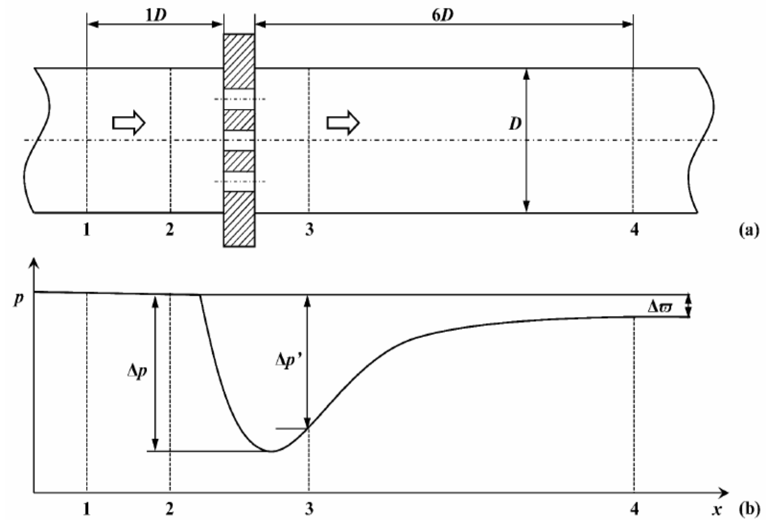


Balance the flow field

Reduce pressure loss

- The existing research on perforated plate balanced flowmeter mainly focuses on the size, number and distribution of **holes**, and the research on **cryogenic fluids** is few.
- The current study is focused on cryogenic fluids, investigate the influence of different working cases and structural features in flow direction.

Bernoulli's principle



Δp : The maximum pressure drop

$\Delta p'$: The actual measured pressure drop

$\Delta\omega$:Permanent pressure loss

Discharge coefficient: $C = \frac{q_v}{q_v'} = \frac{q_v}{\beta^2 A}\sqrt{1-\beta^4}\sqrt{\frac{\rho}{2\Delta p'}}$

Equivalent diameter ratio: $\beta = \sqrt{\frac{A_h}{A}} = \sqrt{\frac{\text{Throttling area of all holes}}{\text{Cross−sectional area of the pipe}}}$

- *C* is the ratio of the actual flow rate to the theoretical flow rate.
- The larger the *C* , the better the performance of the flowmeter.

Pressure loss coefficient: $\zeta = \frac{\Delta\omega}{0.5\rho u^2}$

- Used to measure the permanent pressure loss characteristics of the flowmeter and reflect the energy consumption of the fluid.
- The smaller the ζ, the better the performance of the flowmeter.

3. Numerical Model and Validation

Governing Equations

Mass conservation equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho v_x)+\frac{\partial}{\partial r}(\rho v_r)+\frac{\rho v_r}{\partial r}=0$$

Momentum conservation equation

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_i}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_i}\left(\eta\frac{\partial u_i}{\partial x_i}-\rho u_i' u_j'\right)$$

Energy conservation equation

$$\frac{\partial}{\partial t}(\rho T)+\frac{\partial}{\partial x}(\rho v_x T)+\frac{\partial}{\partial y}(\rho v_r T)=\frac{\partial}{\partial x}\left(\frac{k}{c_p}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{k}{c_p}\frac{\partial T}{\partial x}\right)+S_r$$

κ-ε two equations

(Realizable k-ε turbulence model)

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_j)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_j)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+\rho C_1 S_{k\varepsilon}-\rho C_2\frac{\varepsilon^2}{k+\sqrt{v\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b+S_\varepsilon$$

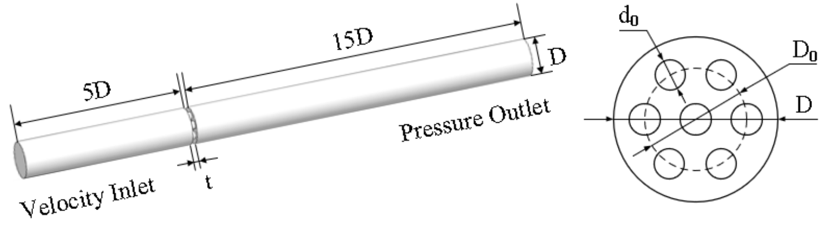
Transport equation for the vapor volume fraction

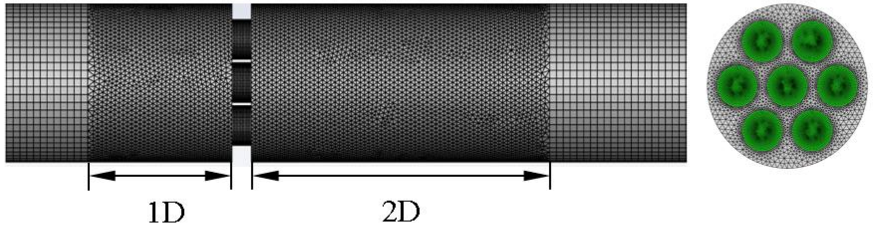
(Schnerr-Sauer cavitation model)

$$p\le p_v(T),\ R_E=3\frac{\rho_v\rho_l}{\rho_m}\alpha_v(1-\alpha_v)\left(\frac{\alpha_v}{1-\alpha_v}\frac{3}{4n}\frac{1}{n}\right)^{-\frac{1}{3}}\sqrt{\frac{2}{3}\frac{p_v(T)-p}{\rho_l}}$$

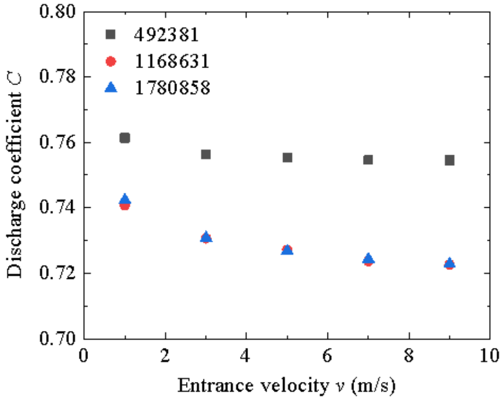
$$p>p_v(T),\ R_C=3\frac{\rho_v\rho_l}{\rho_m}\alpha_v(1-\alpha_v)\left(\frac{\alpha_v}{1-\alpha_v}\frac{3}{4n}\frac{1}{n}\right)^{-\frac{1}{3}}\sqrt{\frac{2}{3}\frac{p-p_v(T)}{\rho_l}}$$

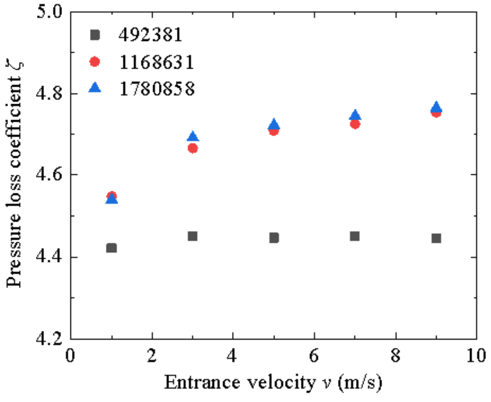
Physical Model and Meshing



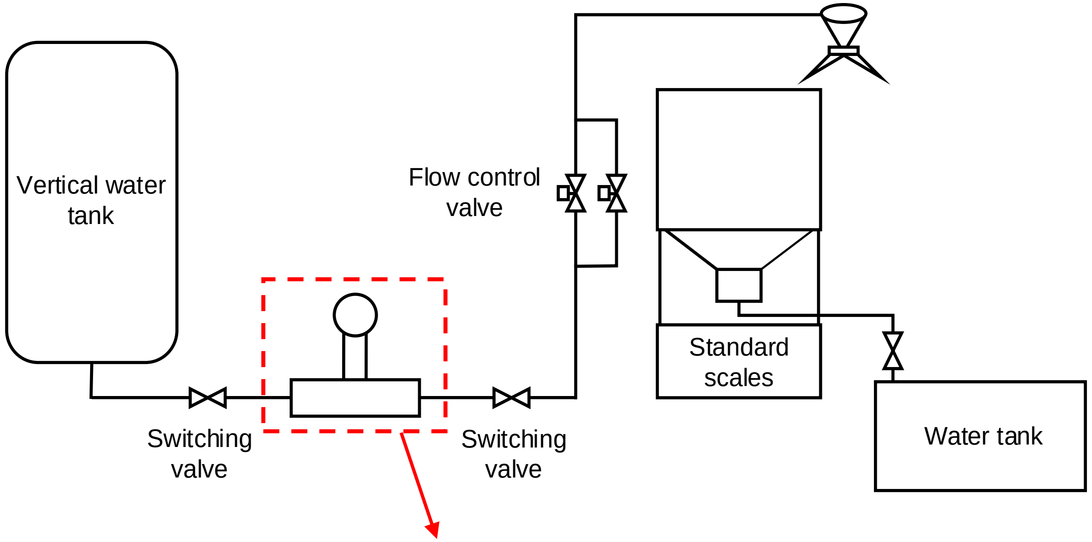


Grid Independence Validation

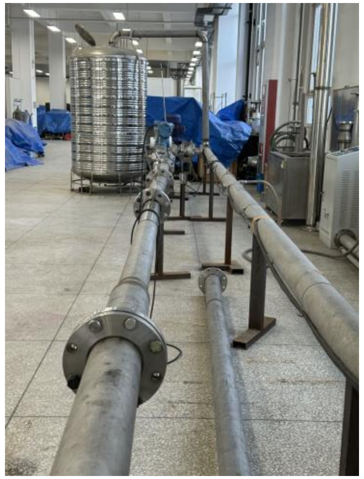


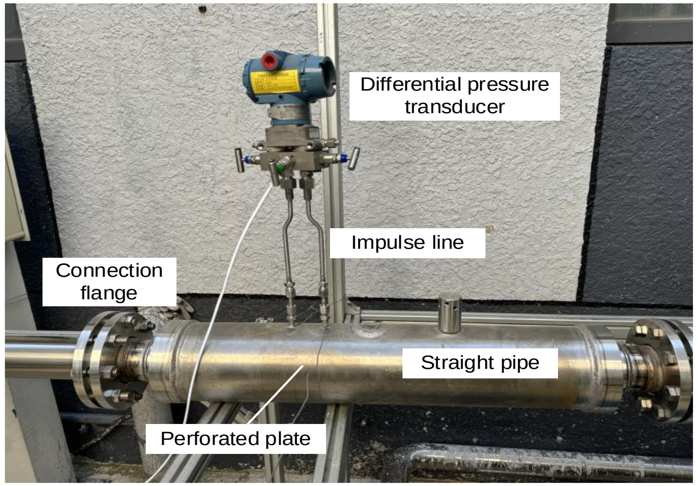


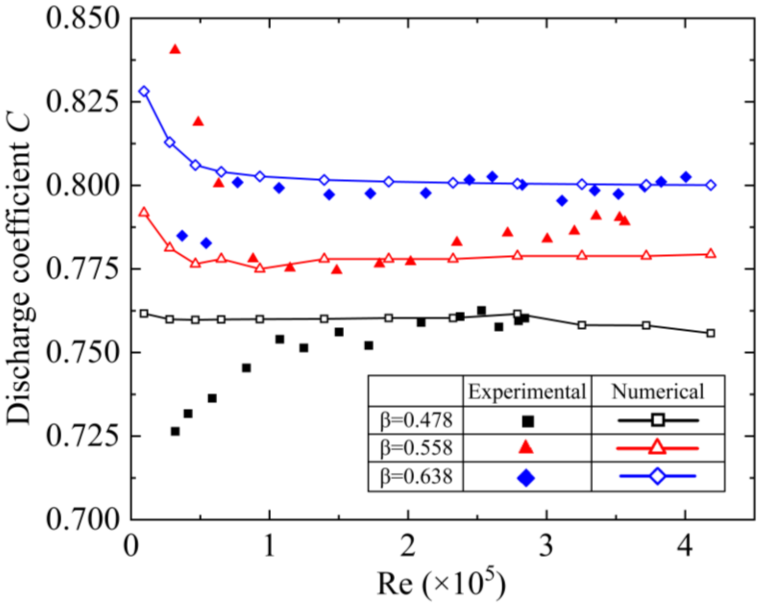
Model Cavitation



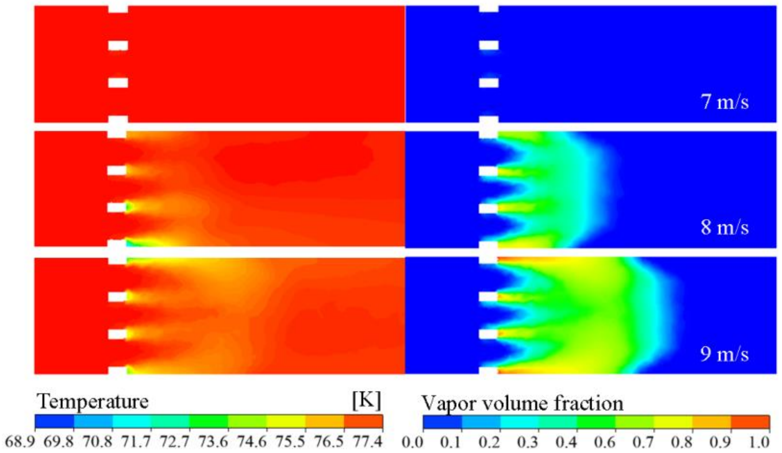
Perforated plates with different β



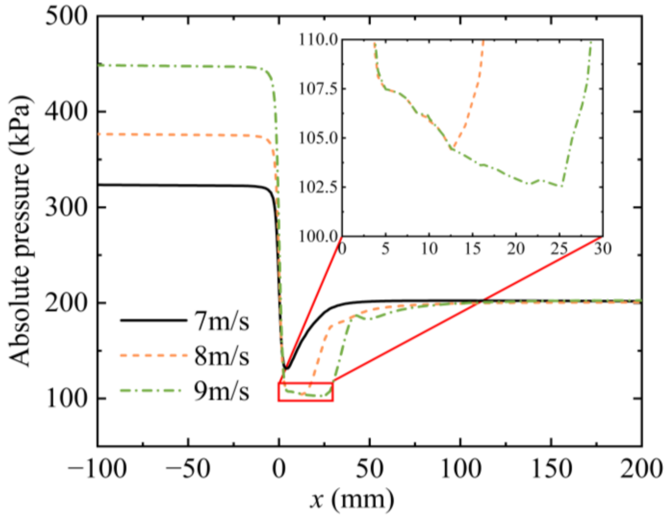




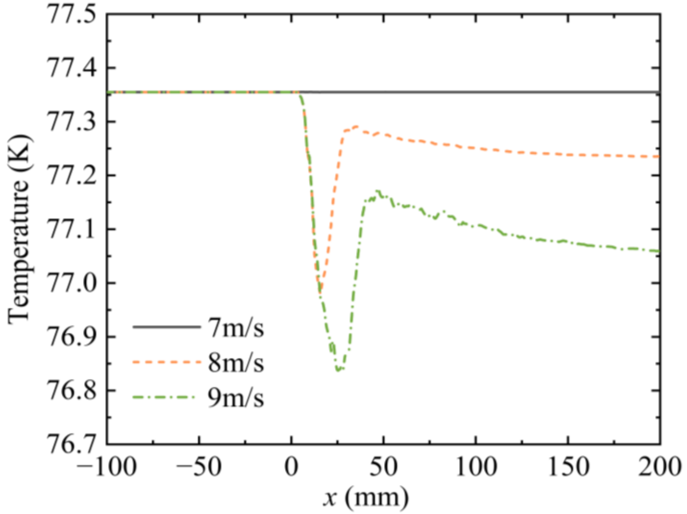
Influence of Inlet Velocity on Cavitation



Contours of temperature and vapor volume fraction



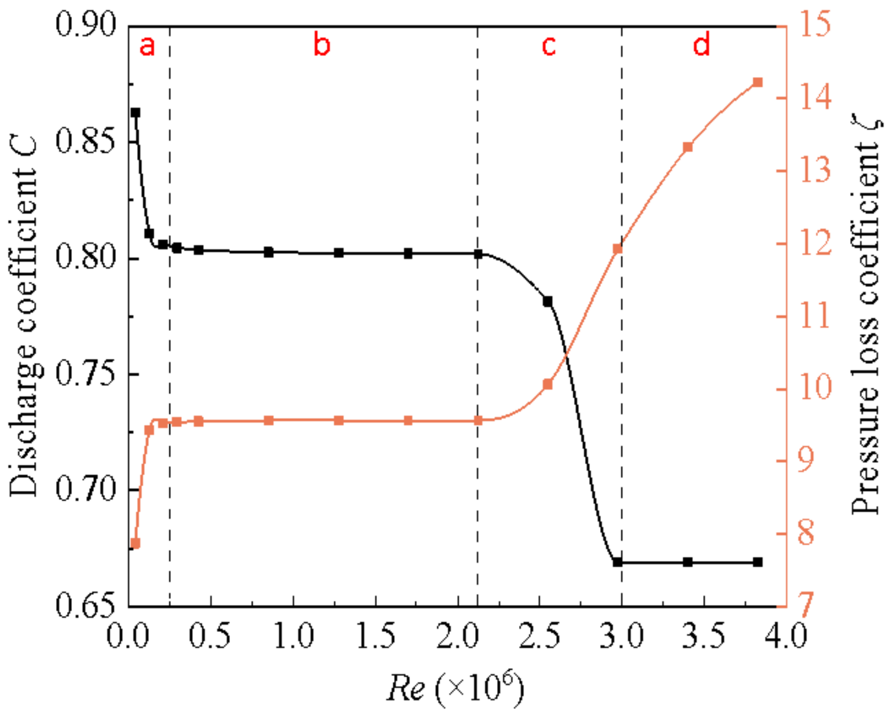
Pressure change on the centreline



Temperature change on the centreline

- Cavitation occurs and result in **gas-liquid two-phase flow** when velocity increasing.
- In the cavitation region, the **thermal effect** of cavitation leads to temperature drop, further affecting the pressure.

Change of Concerned Coefficients



Curves of C and ζ about Re

a. Unstable region

The flow resistance increases with the increase of Re, and the discharge coefficient also increases.

b. Stable region

The discharge and pressure loss coefficient are kept constant, which is also the working region of flowmeters.

c. Cavitation region

The local pressure is lower than the saturated vapor pressure, resulting in cavitation, and the gas-liquid two-phase flow makes the pressure loss increase.

d. Cavitation stable region

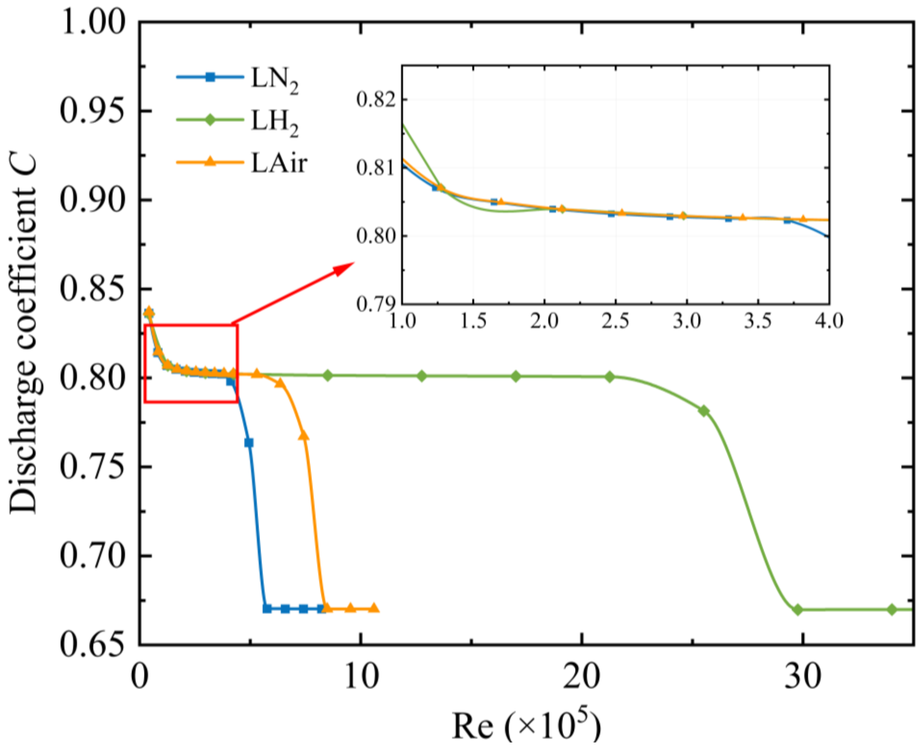
Another line relationship is formed, so the discharge coefficient is stable, but the pressure loss will continue to increase due to the intensification of cavitation.

Types of Cryogenic Fluids

Physical properties	**LN$_2$**	**LH$_2$**	**LAir**
Critical temperature T （K）	77	20	78
Density ρ （kg/m3）	807.7	71.3	879.3
Viscosity μ （mPa·s）	0.1629	0.01391	0.1721
Saturated vapor pressure p_v （Pa）	97152	90717	91294
$\frac{\mu^2}{\rho}$ （kg·mm/s²）	0.0328	0.0027	0.0337

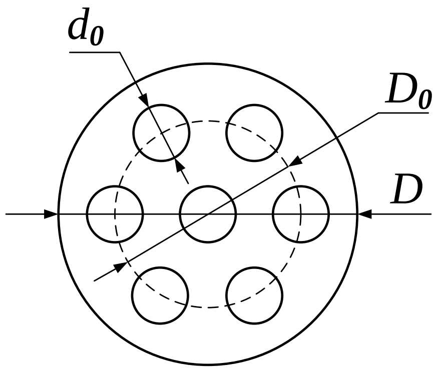
- ➢ The average discharge coefficients of the three fluids in the stable region are basically the same, but the range of stable regions are different.

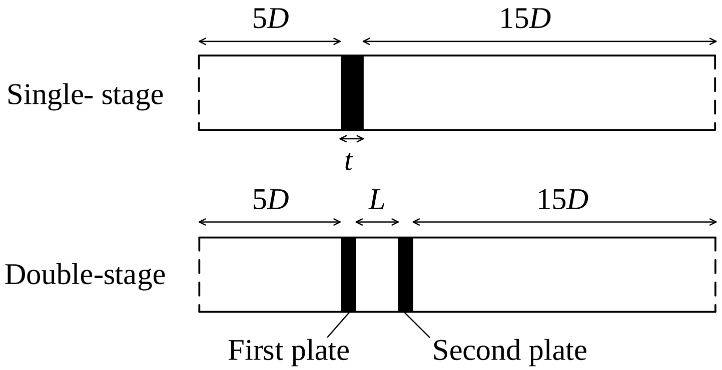
Local pressure drop: $\Delta p = \xi\rho\frac{u^2}{2} = \frac{\xi Re^2}{2D^2}\cdot\boxed{\frac{\mu^2}{\rho}}$



Variation of C for different cryogenic fluids

Structural Features in Flow Direction

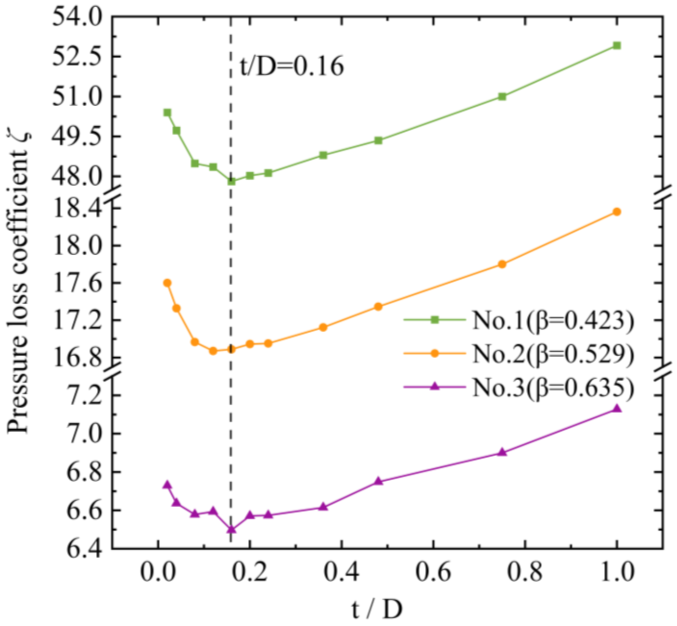




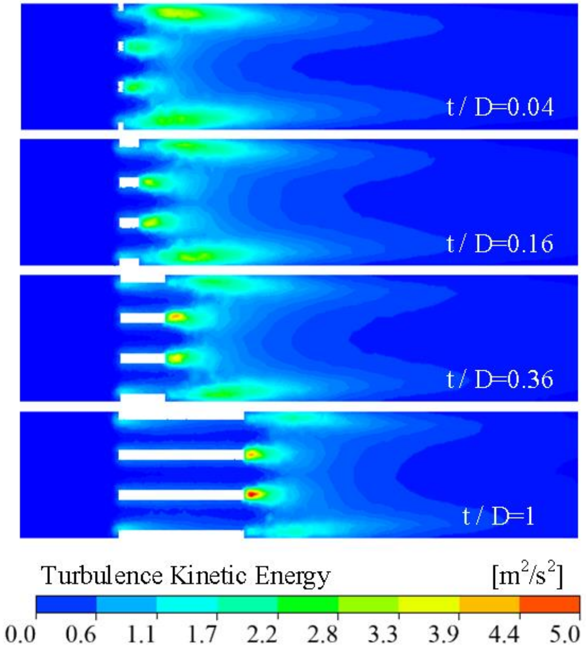
	case	D (mm)	D_0 (mm)	d_0 (mm)	β
Single-stage	No.1	25	16	2	0.423
	No.2			2.5	0.529
	No.3			3	0.635

		t (mm)	First plate	Second plate
Double-stage	No.4	2	No.1	No.1
	No.5		No.1	No.3
	No.6		No.3	No.1
	No.7		No.3	No.3

Single-Stage——Thickness of Plate



Effect of thickness on the ζ of single-stage perforated plate



Turbulence kinetic energy distribution
at different thickness

The vortex with high turbulence kinetic energy gradually transfer from the position near the wall to the center.

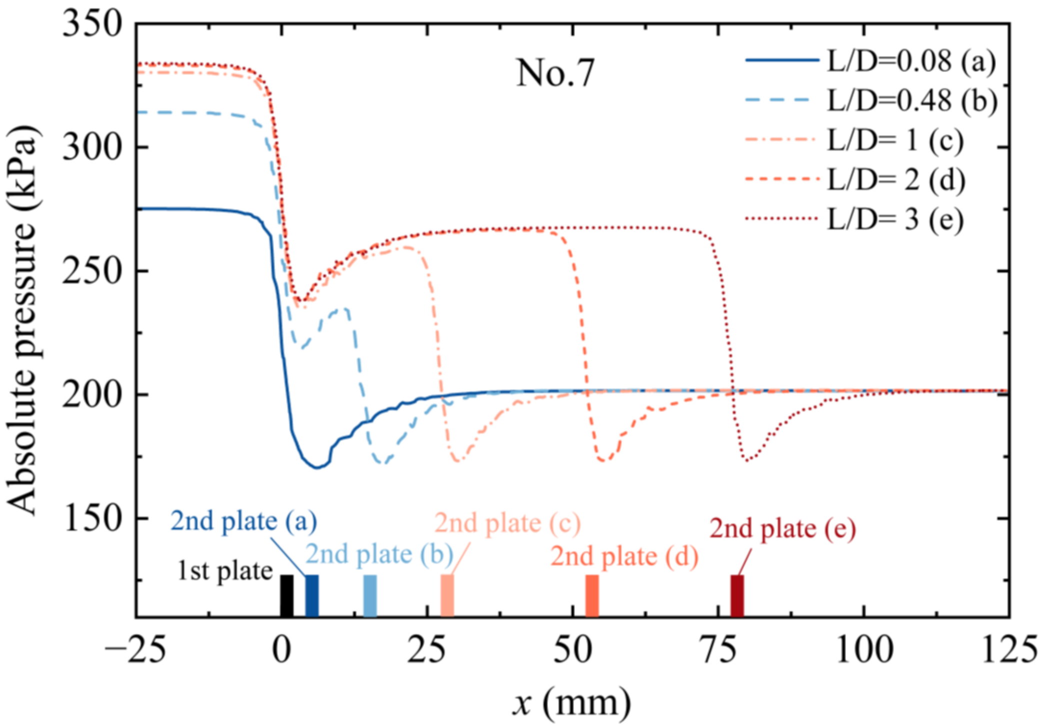
↓

Distribution of turbulence intensity experienced a transition from uneven to even to uneven.

- ➢ Single-stage perforated plate has **the smallest pressure loss coefficient** at t/D=0.16 in different cases.
- ➢ The **local excessive turbulence intensity** results in large pressure loss.

4. Simulation Results and Discussion

Double-Stage——Spacing of Two Plates



Pressure changes on the centreline of No.7 case under different spacings

(a)

- There is not enough space for vortex formation.
- The pressure change **only has a minimum peak,** similar to that of a single-stage.

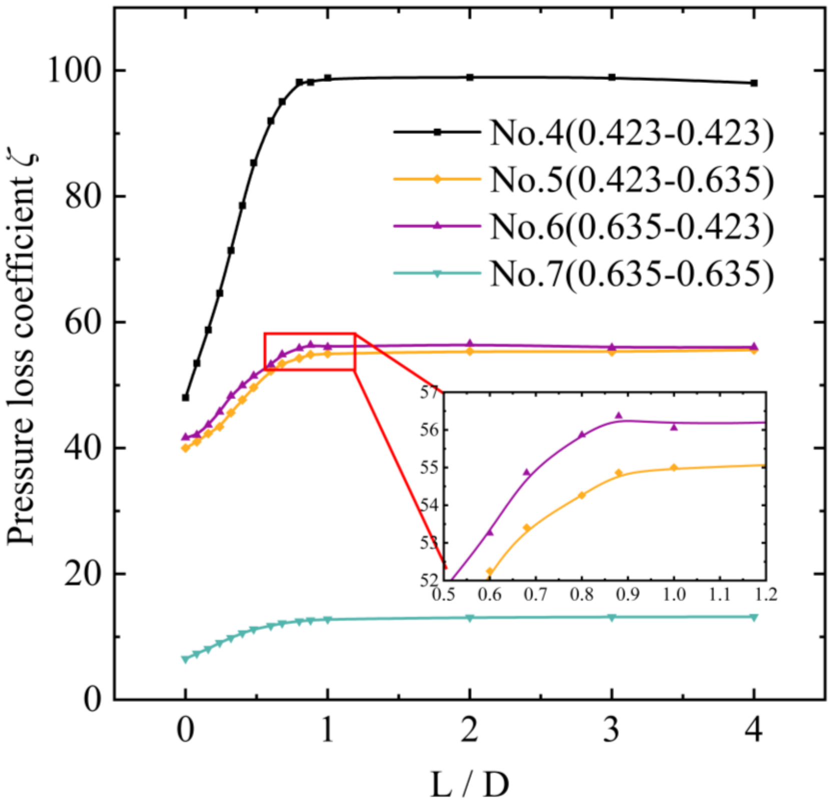
(b)、 (c)

- There is more space for vortex to form and the turbulence intensity increases.
- But the pressure drop generated by the first plate is **not fully recovered** before the second plate.

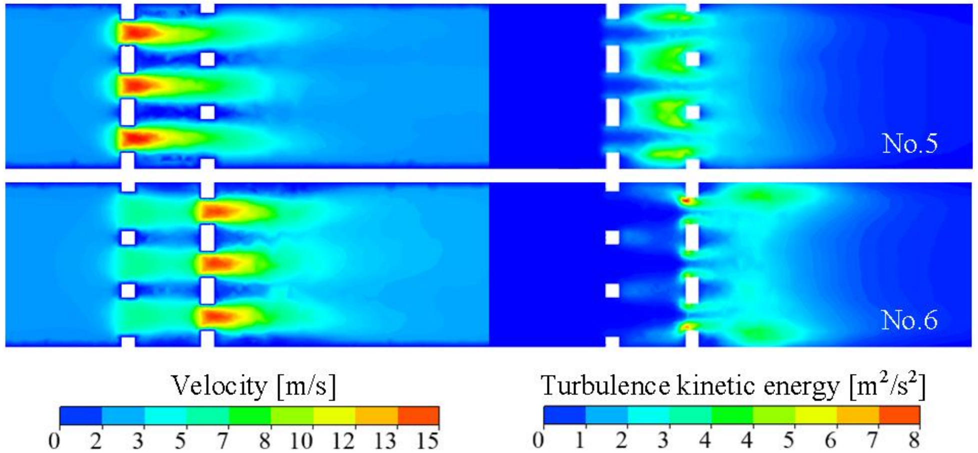
(d)、 (e)

- The spacing of two plates is sufficient for the vortex to develop fully.
- The flow before second plate is closer to the **fully developed**.

Double-Stage——Combination of Two Plates



Effect of spacing on the ζ of double-stage perforated plate



Contours of velocity and turbulence kinetic energy

- Compared to No.5, No.6 has **greater turbulence intensity** at the inlet of second plate, with greater pressure loss.
- The double-stage perforated plate with the combination of **small-large holes** has better performance.

5. Conclusion

◆ Cavitation occurs when the velocity increases to a certain extent, leading to a decrease in temperature, and the occurrence of cavitation is affected by physical properties of different fluids.

◆ The structure of the perforated plate balanced flowmeter mainly affects the pressure loss by changing the magnitude and distribution of turbulence intensity. Reducing turbulence intensity or making its distribution more uniform can benefit the performance of such flowmeter.

◆ For single-stage perforated plates there is an optimal thickness for minimizing its pressure loss. For double-stage perforated plate, using a combination of small-large β can result in lower pressure loss.

Thank you