Performance of V-Cone flowmeter applied to cryogenic fluid measurement considering cavitation

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Abstract. The V-Cone flowmeter is a promising differential pressure flowmeter for metering the cryogenic fluid for its many advantages. When the cryogen velocity increases to a certain value, the cavitation may occur in flowmeter, which may significantly affect the performance of V-Cone flowmeter. However, the effect of cavitation on performance of V-Cone flowmeter remains unclear and there are no published studies to our knowledge on this issue. Here we investigate the performance of V-Cone flowmeter when measuring the cryogenic fluids, especially the effects of cavitation on the discharge coefficient and pressure loss coefficient of the flowmeter. Two cryogenic fluids are investigated, including liquid nitrogen (LN₂) and liquid hydrogen (LH₂). For comparison, the water is also investigated. The realizable κ-ε model is used to describe the turbulence. The Schnerr-Sauer cavitation model is used to investigate the effect of cavitation on the performance of the V-Cone flowmeter. The results show that there was little effect of cavitation on the discharge coefficient and pressure loss coefficient at the initial stage of cavitation. When the cloud cavitation occurred downstream of V-Cone, the discharge coefficient decreases rapidly with Reynolds number increasing, while the pressure loss coefficient rises quickly. The average discharge coefficient is almost the same for different fluids in the stable region; while the cryogenic fluids have wider stable Reynolds number ranges than the water. The lower limits of the Reynolds number for the constant discharge coefficient is very close for three fluids, however, for the upper limits of Reynolds number are quite different. We conclude that measurement range of the cryogenic fluid is much larger than that of the water, which shows that the V-Cone flowmeter exhibits great potential in the measurement of cryogenic fluid. This study provides insights into the effect of cavitation on the measurement of V-Cone flowmeter and opens a new avenue for properly choosing and using a V-Cone flowmeter for metering the cryogenic fluid.

1. Introduction

Cryogenic flow rate measurement and control are fundamentally complex as a result of fluid phase instability. Cryogens are highly susceptible to phase changes resulting from even minute changes in pressure and temperature, particularly when they are near their critical point. The V-Cone flowmeter has been widely used in the measurement of fluids, such as the water, oil and gases. Compared with
the classical differential flowmeter, such as the orifice plate flowmeter, the V-Cone flowmeter not only has advantages including stable signals, wide range ability (10:1 and greater), high accuracy (0.5%) and reliability, short installation requirements (upstream: 0-3D, downstream: 0-2D) and self-cleaning, but also has very low pressure loss [2-4, 6-9]. The pressure loss of V-Cone flowmeter is basically the same as the Venturi flowmeter and far lower than orifice plate flowmeter [6]. All these features make it a promising alternative to the orifice plate flowmeter. Thus the V-Cone flowmeter is a promising differential pressure flowmeter for metering the cryogenic fluid, which is widely used in the field of aerospace application, air separation industry, etc.

The discharge coefficient and pressure loss coefficient of differential pressure flowmeter are two significant performance parameters that determine the measuring accuracy of the flow rate and the energy-saving effect. At present, researchers mainly focus on the effects of the cone angle, the equivalent diameter ratio, the throat length, the upstream disturbed flow, the straight pipe length and the cone installation on the performance of the V-Cone flowmeter. The results showed that compared with the back-cone angle, the front-cone angle of the V-Cone flowmeter is conclusive to the discharge coefficient. Larger front-cone angle can improve the linearity of discharge coefficient as well as increase the pressure loss; the back-cone angle has little effect on the pressure loss [10]. It is found that the V-Cone flowmeter performs better when the front-cone and back-cone angles are between 30° and 60° and between 120° and 150°, respectively [10]. In particular, when the front-cone angle is 45° and the low pressure is obtained from the apex of back-cone, the discharge coefficient is the largest and the linearity of which is the best. To reduce the pressure loss resulted from the vortex behind the V-Cone, the long-waist cone flowmeter with extended throat length was developed. The low pressure ports were located at the annular throat where the pressure was stable, so that the discharge coefficient increased significantly and the measurement accuracy and repeatability were also improved [11]. The long-waist cone flowmeter was also successfully used in the measurement of multiphase flow [12]. The existing research have found that there were little effects of the upstream disturbed flow caused by the upstream elbows, valves, pumps and tees on the discharge coefficient [13, 14]. Therefore, short straight pipes were required for the V-Cone flowmeter. The McCrometer Inc. who invented V-Cone flowmeter recommended 2D and 1D straight pipe length for the upstream and the downstream of V-Cone. But when the diameter ratio was equal to or greater than 0.7, adding another 1D straight pipe length was suggested [4]. Supporting bar and wafer style installations were available for the V-Cone flowmeter [4, 15]. Generally, the measurement accuracy of the supporting bar type was higher than the wafer type due to the low pressure was measured from the apex of back-cone for the former and the single supporting bar had little effect on the flow [4]. In addition, the manufacturing error and the deflection of V-Cone installation also affected the discharge coefficient [16]. Unlike orifice plate and Venturi flowmeter, the V-Cone flowmeter is a non-standard differential meter, its measurement characteristics including the discharge coefficient and the pressure loss coefficient are still under exploring.

As an important dynamic phase-change phenomenon, the cavitation may occur in differential pressure flowmeter when the liquid velocity increased to a certain value leading the static pressure to drop below the vapour pressure of liquid [17]. The cavitation may induce material erosion, mechanical vibration and noise and seriously affect the performance as well as the structural integrity of flowmeter. Flow cavitation has been investigated extensively in differential pressure devices, including orifice plates, Venturi tubes and Venturi nozzles. Numachi et al. [18-19] investigated different orifice plates and Venturi tubes under cavitating conditions. They reported that the cavitation affected the orifice discharge coefficient little when the cavitation number is no less than 0.2 [18]. The effect of cavitation on the discharge coefficient and the pressure loss coefficient of Venturi tubes is also small when the cavitation number more than 0.06 [19]. Ramamurthi and Nandakumar [20] investigated the discharge coefficient of sharp-edged cylindrical orifices flowing with water, they found that the discharge coefficient depended on the orifice diameter for cavitating flows. Ebrahimi et al. [21] explored the cavitation characteristics of through a thick orifice plate. A critical downstream-to-upstream pressure ratio of 0.45 was identified below which cavitation and flow choking will occur.
Ashrafizadeh and Ghassemi [22] conducted experiments using water to investigate the effect of the upstream and downstream pressures and the geometrical parameters on the mass flow rate through cavitating Venturi. They obtained the critical pressure ratio at the cavitation condition with the maximum upstream pressure of 2MPa. Tomov et al. [23] observed the cavitation regimes of water in a horizontal Venturi nozzle, and three cavitation regimes, i.e., cloud cavitation, quasisuper cavitation and super cavitation were reported. Long et al. [24] investigate the global cavitation behaviour in a Venturi tube. They found that once cavitation occurs, the flow rate remains almost constant regardless of the outlet pressures variations, and the pressure ratio and cavitation number are linearly related. Liu et al. [25] and Jin et al [26] investigated the performance of the perforated plate flowmeter for metering the cryogenic fluid by simulation. They found that the upper limit of Reynolds number of the perforated plate is significantly dependent on the properties of the measured fluid.

At present, much less is known about the effect of cavitation on V-Cone flowmeter and there are no published studies to our knowledge on this issue, especially the performance of V-Cone flowmeter applied to the cryogenic fluid measurement. When the cryogenic velocity increases to a certain value, the cavitation may occur in flowmeter, which may significantly affect the performance of V-Cone flowmeter. However, the effect of cavitation on performance of V-Cone flowmeter remains unclear and there are no published studies to our knowledge on this issue. This limits the further popularity and applications as well as the standardization of the V-Cone flowmeter. The objective of this study is to investigate the effects of cavitation on the measurement of V-Cone flowmeter. Two cryogenic fluids (liquid nitrogen (LN₂) and liquid hydrogen (LH₂)) and the water are investigated. The numerical method is validated against the experimental results, and then the appropriate cavitation model is determined; the discharge coefficient and pressure loss coefficient of the V-Cone flowmeter are concluded with increase of inlet liquid velocity. The effects of cavitation on the discharge coefficient and pressure loss coefficient of the V-Cone flowmeter are analyzed. We also discuss the possible reasons that caused the different characteristics of the V-Cone flowmeter when metering the cryogenic fluid and water.

2. V-Cone flowmeter

A typical V-Cone flowmeter is shown in figure 1(a). The primary elements are two connected “V” shaped cones (i.e., the front-cone and the back-cone), creating the restriction. The V-Cone element is held by a supporting bar and positioned in the center of the pipe leaving an annular opening. The front-cone and back-cone angles are 45° and 135°, respectively. As shown in figure 1(b), the low pressure is measured from the low pressure port connecting with the apex of the back-cone and passing through the V-Cone and the supporting bar. The high pressure port is located on the upstream of V-Cone. In the present case, the inside diameter of the V-Cone flowmeter inlet, D, is 50 mm and the equivalent diameter ratio, β, is 0.45. The flowmeter is positioned horizontally.

![Figure 1. Geometry of V-Cone flowmeter (a) typical V-Cone flowmeter (by courtesy of Fuji Electric France) (b) V-Cone structure.](image-url)
As a typical differential pressure flowmeter, when used to meter the liquid, the mass flow rate equation of the V-Cone flowmeter can be concluded according to the mass continuity equation and the Bernoulli equation (assume that the liquid is incompressible), as shown in equation (1):

\[ m_l = \frac{C_d \pi}{4} D^2 \beta^2 \sqrt{2 \rho_l \Delta P} \]

\[ = \frac{C_d A \sqrt{2 \rho_l \Delta P}}{\sqrt{1 - \beta^2}} \]  

(1)

where \( m_l \) is the liquid mass flow rate, \( \Delta P \) is the actual differential pressure of the V-Cone flowmeter, \( \beta = \sqrt{A/A_m} = \sqrt{(D^2 - d^2)/D^2} \) is the equivalent diameter ratio, and defined as the square root of the ratio of the minimum cross sectional area \( A_m = \pi (D^2 - d^2)/4 \) to the inlet area \( A = \pi D^2/4 \) of the V-Cone flowmeter, \( d \) is the diameter of V-Cone, \( \rho_l \) is the liquid density and \( C_d \) is the discharge coefficient.

The discharge coefficient \( C_d \) is one of the important parameters affecting the performance of the V-Cone flowmeter. \( C_d \) is mainly determined by the geometry of the V-Cone and the Reynolds number \( (Re) \). When \( Re \) increases to a certain value, \( C_d \) will be independent of it, which means it is approximately a constant. The measurement range of a V-Cone flowmeter is determined by \( C_d \).

Generally, a larger \( C_d \) is expected to reduce the pressure loss of the V-Cone flowmeter. According to equation (1), the discharge coefficient \( C_d \) can be expressed as equation (2).

\[ C_d = \frac{m_l \sqrt{1 - \beta^2}}{A \sqrt{2 \rho_l \Delta P}} \]

(2)

Hence, \( C_d \) is calculated with mass flow rate \( (m_l) \), the equivalent diameter ratio \( (\beta) \), the minimum cross sectional area \( (A) \), the liquid density \( (\rho_l) \) and the measured differential pressure \( (\Delta P) \).

Another important parameter characterizing the performance of the V-Cone flowmeter is the pressure loss coefficient \( (\zeta) \) [27]. It is defined by equation (3).

\[ \zeta = \frac{\Delta \tilde{p}}{\rho_l U_i^2 / 2} \]

(3)

where \( \Delta \tilde{p} \) is the permanent pressure loss consisted of the pressure loss along the pipe and the local pressure loss produced by the metering element [5, 6], and \( U_i \) is the mean liquid velocity.

The permanent pressure loss is obtained by measuring the differential pressure between the upstream of the V-Cone and the pressure recovery position downstream of the V-Cone.

3. Numerical methods

3.1 Simulation scheme

Ignoring the effect of supporting bar on the measurement, the flow domain can be simplified into 2D computation domain due to the symmetry of the V-Cone flowmeter. As shown in figure 2, the geometry consists of three parts, i.e. the upstream pipe, the V-Cone section and the downstream pipe. The upstream straight pipe length is five times the pipe diameter \( (5D) \) from the front apex of the V-Cone and the downstream straight length is \( 9D \) downstream from the end of the V-Cone, which enables the flow to fully develop and the pressure building to be finished. The flow domain is meshed with quadrilateral meshes and they are densified around the cone body and in the region proximate to the wall to achieve higher accuracy and better convergence.
3.1.1. Turbulence model. Five types of turbulence models, i.e., the Standard $k$-$\varepsilon$ Model (SKE), the Renormalization Group $k$-$\varepsilon$ Model (RNGKE), the Realizable $k$-$\varepsilon$ Model (RLKE), the Standard $k$-$\omega$ Model (SKW) and the Shear Stress Transport $k$-$\omega$ Model (SSTKW), are compared in the present simulation [28]. Figure 3 demonstrates that the pressure distributions on the pipe wall are different under different turbulence models, especially that downstream of the V-Cone. Between 0D and 3D downstream V-Cone, the pressure predicted by the SKE model is higher than that of by other four turbulence models, followed by the RLKE model, the RNGKE model and the SSTKW model, while the SKW model is the lowest. According to the experimental results, the RLKE model performs best among the five turbulence models. Moreover, the RLKE model is also used in other types of differential pressure devices [25, 26, 29-31]. Consequently, the RLKE model is employed in the present study.

3.1.2. Solving strategies. The steady simulations are conducted. The mixture multiphase flow model is adopted. Assuming that the vapour phase and liquid phase are homogeneously mixed in cavitation region, there is no need to solve for the slip velocity. As shown in figure 2, the velocity inlet boundary condition is used to define the liquid flow rate at the flow inlet and the pressure outlet boundary condition is adopted at the end of the pipeline. The turbulence intensity at the inlet and outlet is dependent on the empirical correlation for fully-developed duct flows. In the pressure-velocity coupling, the Coupled scheme is used for quick convergence. For the spatial discretization, the pressure is calculated by PRESTO!, the momentum, energy, volume fraction, turbulent kinetic energy and turbulent dissipation rate are calculated by QUICK. To improve the solution behaviour of flow simulations when higher order spatial discretizations are used, the High Order Term Relaxation method is employed. The convergence criteria are assumed to be met when the iteration residuals are reduced to $10^{-6}$ and the mass flow rates of the inlet and outlet are equal.
3.2. Cavitation model

Three cavitation models, i.e., the Schnerr and Sauer model, the Zwart-Gerber-Bleamri model and the Singhal et al. model, are available in cavitation simulation in the ANSYS FLUENT [27]. The Schnerr and Sauer model has been widely used in the cavitation simulation of differential pressure devices, such as orifice plate, the Venturi, the nozzle and so on [25, 26, 29-31]. The results showed that this model performed well against the experimental data as well as possessed advantages of stable and easy convergence. Thus the Schnerr and Sauer model is employed in the present study. Schnerr and Sauer follow the approach of Singhal et al. to derive the exact expression for the net mass transfer from liquid to vapour [32]. The equation for the vapour volume fraction has the form as follows:

\[ \nabla \cdot (\alpha \rho \tilde{v}_e) = R_v - R_c \]  \hspace{1cm} (4)

where \( \alpha \) is the vapour volume fraction, \( \rho \) is the vapour density, \( \tilde{v}_e \) is the velocity of gaseous phase, \( R_v \) and \( R_c \) are the evaporation rate and condensation rate, respectively, which are expressed by equations (5) and (6).

\[ p \leq p_c, \quad R_v = \frac{\rho_v \rho_l \alpha(1-\alpha)}{\rho_l^2} \frac{3}{R_b^3} \frac{2(p_c - p)}{\rho_l} \]  \hspace{1cm} (5)

\[ p > p_c, \quad R_c = \frac{\rho_v \rho_l \alpha(1-\alpha)}{\rho_l^2} \frac{3}{R_b^3} \frac{2(p - p_c)}{\rho_l} \]  \hspace{1cm} (6)

where \( P \) is the statistic pressure on the vapour, which is a function of temperature, and \( P \) is the statistic pressure at the far field, \( \rho_l \) is the liquid density, \( R_b \) is the bubble radius, and is shown as equation (7).

\[ R_b = \left( \frac{\alpha}{1-\alpha} \frac{3}{4\pi n_b} \right)^{\frac{1}{3}} \]  \hspace{1cm} (7)

where \( n_b \) is the number of bubbles per volume of liquid.

Note that an UDF is added into the energy equation (equation (8)) to take into account the effects of latent heat of vaporization.

\[ \rho_m \mu_m \nabla T = \nabla \cdot \left( \lambda_m \nabla \lambda_m + \lambda_t \nabla I \right) + S_E \]  \hspace{1cm} (8)

where \( \rho_m \) is density of gas and liquid mixture, \( \lambda_m \) is the mass average velocity, \( I \) is the unit tensor, \( T \) is the temperature, \( \mu_m \) is the dynamic viscosity of mixture, \( \mu_t \) is the turbulent viscosity, \( \lambda_m \) is the heat conductivity of mixture, \( \lambda_t \) is the turbulent heat conductivity and \( S_E \) is the volume heat source considering the mass transfer and the latent heat of vaporization.

3.3. Model validation

Four groups of meshes are used to check the grid independence. The cell numbers from 60, 800 to 150, 240 are used and finally the mesh with 122, 000 cells is adopted. The experiments of the ogive cavitation in a plastic tunnel conducted by Hord [33] from NASA are used to validate the cavitation model. The computational domain of the ogive is shown in figure 4. The simulations of liquid nitrogen (LN\(_2\)) and liquid hydrogen (LH\(_2\)) cavitation through the axisymmetric ogive numbered 304D and 349B are conducted. The boundary conditions are listed in table 1. In the simulation, a uniform velocity is specified at the inlet, and a pressure is set at the outlet. Both the RLKE model and the Schnerr-Sauer cavitation model are activated. As shown in figure 5, compared with the experimental data, the numerical values are acceptable for both the LN\(_2\) and LH\(_2\), considering the instrumentation uncertainty of 6900 Pa for pressure and 0.2 K for temperature.
Figure 4. Computational domain of the ogive.

Table 1 Boundary conditions for ogive 304D and 349B [33].

| No. | Liquid | Free-stream temperature, $T$ (K) | Free-stream velocity, $U$ (m·s$^{-1}$) |
|-----|--------|----------------------------------|-------------------------------------|
| 304D | LN$_2$ | 78.1                             | 10.8                                |
| 349B | LH$_2$ | 21.33                            | 63.9                                |

Figure 5. Pressure and temperature distributions along the ogive wall (a) pressure distribution of LN$_2$ (b) temperature distribution of LN$_2$ (c) pressure distribution of LH$_2$ (d) temperature distribution of LH$_2$.

4. Results and discussions

After validation, the simulation mainly focuses on two cryogenic fluids and one water, i.e., liquid nitrogen (LN$_2$), liquid hydrogen (LH$_2$) and water around the normal temperature (23$^\circ$C). Table 2 lists the inlet free-stream temperature, outlet pressure, saturated vapor pressure, density, and kinematic viscosity of saturated liquid corresponding to the inlet free-stream temperature for the three fluids for the simulation. For LN$_2$ and LH$_2$, the inlet free-stream temperatures are set as their normal boiling point temperatures, while ambient temperature is considered for Water.

Table 2 Conditions and corresponding properties of the fluids.

| Liquid | Inlet free-stream temperature, $T$ (K) | Outlet pressure, $P$ (MPa) | Saturated vapor pressure, $P_v$ (Pa) | Liquid density, $\rho$ (kg·m$^{-3}$) | Liquid kinematic viscosity, $\nu$ (cm$^2$·s$^{-1}$) | $\rho\nu^2$ ($\times$10$^6$) kg·cm$^{-2}$·s$^{-2}$ |
|--------|---------------------------------------|---------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| Water  | 296.15                                | 0.2                       | 2811.1                              | 997.5                               | 0.009345                           | 0.08711                            |
| LN$_2$ | 77.36                                 | 0.2                       | 101385                               | 806.08                              | 0.001993                           | 0.00320                            |
| LH$_2$ | 20.37                                 | 0.2                       | 101358                               | 70.85                               | 0.001880                           | 0.00025                            |

4.1. Discharge coefficient

The variations of the discharge coefficient ($C_d$) of V-Cone flowmeter with Reynolds number (Re$_f$) were shown in figure 6. We found that $C_d$ depended on Re$_f$ when Re$_f$ was small. $C_d$ was close to constant as Re$_f$ increased to a “stable region”, which was preferred for the flow rate measurement according to equation (1). With further increase of Re$_f$, the cavitation occurred as shown in figure 7.
However, unlike the perforated plate flowmeter whose discharge coefficient will drop abruptly when the cavitation occurred [25, 26], the $C_d$ of V-Cone flowmeter held constant when the cavitation was at the initial stage. This is because the low pressure of the V-Cone flowmeter is obtained from the apex of the back-cone (see figure 1) and the cavitation occurred in the downstream of the V-Cone has little effect on it (figure 7). If further increased $Re$, the cloud cavitation occurred downstream of V-Cone and $C_d$ decreased owing to the decrease of pressure drop ($\Delta P$) resulted from the occurrence of vapour-liquid two-phase flow in cavitation.

The flow measurement equation (equation (1)) suggests that a stable discharge coefficient $C_d$ is significant for the V-Cone flowmeter. The approximate ranges of $Re_i$ for the stable region of the three fluids obtained from figure 6 are listed in Table 3 with the corresponding average discharge coefficient $\overline{C_d}$ and the standard deviations $\sigma$. It can be seen that $\overline{C_d}$ was almost the same for all the three fluids in the stable region, whereas the ranges of $Re_i$ were different. The critical Reynolds number $Re_c$ [25, 34], which is the lower limits of the $Re_i$ for the constant discharge coefficient, was very close for three fluids. It proves that the $Re_c$ is determined mainly by the geometry of the V-Cone flowmeter and less affected by the properties of the fluids. However, for the upper limits of Reynolds number (denoted as $Re_{cp}$), there are quite large differences for diverse fluids, with a minimum of $3.47 \times 10^5$ for Water and a maximum of $47.87 \times 10^5$ for LH2. In addition, the values of standard deviation indicate that the discharge coefficient has a good stability in the stable region for the three fluids.

Note that although the $C_d$ of V-Cone flowmeter can hold constant before severe cavitation occur downstream of V-Cone, the V-Cone flowmeter is not recommended to use under cavitation condition owing to the disadvantages of the cavitation erosion, the mechanical vibration and noise and the increased pressure loss resulted from cavitation. The turndown ratio of the present V-Cone flowmeter with and without cavitation is shown in table 3. We found that measurement range of the cryogenic fluid was much larger than that of the water. The V-Cone flowmeter exhibits great potential in the measurement of cryogenic fluid.

![Figure 6. Variation of discharge coefficient with Reynolds number $Re_i$, the cavitation under different $Re_i$ is shown in figure 7.](image)

| Fluid | Range of $Re$ (x$10^5$) | $\overline{C_d}$ (x$10^{-3}$) | $\sigma$ (x$10^{-3}$) | Turndown ratio (without cavitation) | Turndown ratio (with cavitation) |
|-------|-------------------------|-----------------------------|----------------------|-----------------------------------|-------------------------------|
| Water | 0.27-3.47               | 0.860                       | 0.9                  | 8:1                               | 13:1                          |
| LN₂   | 0.25-13.17              | 0.862                       | 1.4                  | 32:1                              | 53:1                          |
| LH₂   | 0.27-47.87              | 0.862                       | 1.3                  | 103:1                             | 177:1                         |
The differences of the fluid properties may be the reasons for the different $Re_{up}$ values [25]. The pressure drop of the fluid through the V-Cone can be calculated by [35]

$$\Delta P = \xi \rho \frac{U^2}{2}$$  \hspace{1cm} (9)

where $\xi$ is the resistance coefficient, depending on the geometry of the V-Cone. Equation (9) can be rewritten as

$$\Delta P = \frac{\xi Re^2}{2D^2} \rho v^2$$  \hspace{1cm} (10)

We can see from equation (10) that, for a given $Re_l$, the pressure drop caused by the V-Cone is proportional to the product of the density and the squared kinematic viscosity, i.e., $\rho v^2$. According to table 2, the cryogenic liquids (LN$_2$ and LH$_2$, especially LH$_2$) have smaller values of $\rho v^2$ compared with water. Therefore, with a fixed $Re_l$, the pressure drops through the V-Cone for these cryogenic fluids are much less than that for water. In addition, the saturated vapor pressures $P_v$ of the two cryogenic fluids in present study are almost equal to the atmospheric pressures because the temperatures of the fluids are set at the normal boiling point temperatures. Thus, the occurrence of cavitation is more difficult for the cryogenic fluids under comparable thermofluid dynamic conditions, i.e., the same pressure at the outlet section. As for Water around the ambient temperature, its saturated vapour pressure is lower than those of the cryogenic fluids at their normal boiling temperatures; however, the much larger pressure drop due to the much larger $\rho v^2$ of Water leads to the occurrence of cavitation at relatively low $Re_l$, i.e., low $Re_{up}$, in comparison with the two cryogenic fluids.
Figure 7. Gas volume fraction (GVF) under different Reynolds number (Re) when the working fluid is (a) Water, (b) LN$_2$ and (c) LH$_2$.

4.2. Pressure loss coefficient
Similar to the discharge coefficient as shown in figure 6, the pressure loss coefficient $\zeta$ is also affected by the Re$_i$ (see figure 8). The pressure loss coefficient is first decreased with Re$_i$ increasing and then approximate to a constant. The occurrence of cavitation seems has little effects on the flow resistance, which did not result in a marked rise in the pressure loss coefficient. However, when the cloud cavitation occurs downstream of V-Cone, the liquid/vapour two-phase flow caused by the cavitation increases the flow resistance, and thus makes the pressure loss coefficient increase dramatically. A lower permanent pressure loss, indicated by the smaller pressure loss coefficient, is beneficial for the flowmeter application. It is found that the constant pressure loss coefficient is almost not affected by the type of fluid. However, for the investigated cryogenic fluids, especially LH$_2$, the pressure loss coefficient can remain constant even in the case of much larger Re$_i$. This can be attributed to the larger Re$_{cap}$ related to the effects of cavitation on the discharge coefficient, as mentioned in Section 4.1.

![Figure 8](image.png)

Figure 8. Variation of pressure loss coefficient with Reynolds number.

5. Conclusions
Numerical studies were carried out in this paper to investigate the performance of V-Cone flowmeter when measuring the cryogenic fluid (LN$_2$ and LH$_2$) and water around the ambient temperature. The discharge coefficient $C_d$ and the pressure loss coefficient $\zeta$ of V-Cone flowmeter with the same pressure at the outlet section were analysed. Emphasis was put on the effect of cavitation on the discharge coefficient and pressure loss coefficient. Based on the numerical simulations, the main conclusions are as follows:

1) As Reynolds number Re$_i$ increased, $C_d$ and $\zeta$ were dependent of it at first and then almost constant. There was little effect of cavitation on the $C_d$ and $\zeta$ at the initial stage of cavitation, which was preferred for the flow rate measurement. When the cloud cavitation occurred downstream of V-Cone, $C_d$ decreased rapidly with Re$_i$ increasing, while $\zeta$ rose quickly. Because the cavitation may cause local surface fatigue failure and the subsequent detachment or flaking off of pieces of material as well as the vibration and noise, so we should avoid the cavitation damage in practical applications.

2) The average discharge coefficient $\bar{C}_d$ is almost the same for different fluids in the stable region, while the cryogenic fluids have wider stable Re$_i$ ranges than the water. The lower limits of the Re$_i$ for the constant discharge coefficient, is very close for three fluids, however, for the upper limits of Reynolds number are quite different. We conclude that measurement range of the cryogenic fluid is much larger than that of the water. The V-Cone flowmeter
exhibits great potential in the measurement of cryogenic fluid.

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