Cavitation characteristics and suppression research of refrigerant in capillary tube

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Abstract—Cavitation is easy to form and develop due to the large pressure drop during throttling in the refrigeration system. To effectively suppress the throttling cavitation phenomenon, an aerating method through bypass capillary is proposed. Based on the Homogeneous Equilibrium Mixture (HEM) model, the Schnerr-Sauer cavitation model and the Realizable k-ε turbulence model were adopted, and the throttling process in the capillary tube and transition tube was simulated by Fluent, and the pressure distribution and vapor volume fraction distribution in the capillary tube and transition tube were obtained for both original model and aerating model. Results show that after adopting the aerating technology, the vapor volume fraction at the capillary outlet is almost unchanged, while the vapor volume fraction in the transition tube is obviously increased, which indicates that the bubble collapsing phenomenon in the transition tube is weakened, and then realized the purpose of suppressing the cavitation effect.

1. Introduction

Cavitation is a phenomenon with explosive growth and collapse of microbubbles, which caused by vaporization of liquid due to the fact that the local liquid pressure is lower than the saturated pressure at the corresponding temperature [1]. When the liquid flow downstream, those bubbles carried by the main fluid will collapse due to the higher pressure there. Cavitation is a typical unsteady process with vapor-liquid two-phase flow. There is a very complicated momentum and energy exchange relationship between bubbles and liquid. Cavitation generally occurs in hydraulic machinery such as inducers, turbo pumps, nozzles, water turbines, and ship propellers [2-3], as well as throttling devices such as valves, venturis, and nozzles [4-5]. Cavitation is almost inevitable due to the variation of flow cross-sectional area at the outlet of the refrigeration throttling device and the two-phase state of fluid. In particular, the pressure and temperature gradient between the inlet and the outlet of the throttling device is relatively large, which facilitates the development of cavitation [1]. Cavitation can cause serious destructive problems. Long-term cavitation flow will not only cause waste of energy, but also reduce the life of components and cause system imbalances, which in turn will cause complex noise excitation. Therefore, it is necessary to study the flow and cavitation characteristics in the refrigeration throttling device.

In the process of cavitation, the flow characteristics are complicated, owing to the mass transfer between vapor and liquid phases, and also contains two-phase flow and turbulence. Relative studies have been carried out from two aspects including experimental analysis and numerical simulation, which is helpful for in-depth understanding of the physical characteristics of cavitation dynamics. Zhu et al. [6] established a numerical simulation framework for unsteady cryogenic cavitation considering the thermal effect and compressibility of vapor and liquid, revealed the coupling mechanism of thermal effect, vorticity, and cryogenic cavitation, and investigated the frequency and pressure fluctuation.
characteristics and mechanism of liquid hydrogen flowing through hydrofoil in the process of cavitation

In recent years, researchers have realized the suppression of hydraulic cavitation and noise by using aerating structure. Peterka et al. [8] found that the cavitation effect in the pipeline will be weakened and the corresponding noise will be reduced when the aerating vapor concentration reaches a certain level. Mäkiharju et al. [9] studied the completely detached cavity formed in the wedge-shaped downstream separation flow area. The experimental results showed that when a relatively small amount of vapor enters the shear layer at the cavity interface, the generation of vapor can be suppressed and then the cavitation effect can be suppressed. Dong et al. [10] conducted an experimental study on the aerating characteristics in the cavitation zone of high-speed water flow based on the compressibility theory, and proposed a semi-cubic parabolic relationship between the minimum aerating concentration to suppress cavitation and the flow velocity. The research shows that aerating technology improves the pressure in local area, so as to suppress cavitation effect and greatly reduce the cavitation noise in water conservancy and hydropower projects [11] and hydraulic throttle valve [12]. In general, the commonly used cavitation suppression methods mainly include two-stage (or multi-stage) throttling, optimization of component structure, and aerating technology. Their essence is to improve the pressure distribution in the area where cavitation occurs, because the pressure distribution has a great influence on the shape and intensity of cavitation [13].

For a long time, the study on the complex and variable process of cavitation phenomenon has been explored, and the working fluid of experimental and theoretical analysis is mostly water [14]. In recent years, the research results on the throttling cavitation of cryogenic fluid have been increasingly enriched [4-7]. Compared with water, the refrigerant has lower saturation temperature and smaller latent heat of vaporization, and is more prone to cavitation due to its rapid temperature increase and large pressure gradient. At present, there are few studies focused on the occasional sharp noise in capillary caused by two-phase cavitation flow in refrigeration system. The research on the combination of throttling injection and cavitation in refrigeration system has not been involved, and there are few studies on the cavitation dynamic characteristics of vapor-liquid two-phase flow at the outlet of throttling device. Ingle et al. [15], Alok et al. [16], and Prajapati et al. [17] analyzed the flow characteristics in adiabatic capillary with numerical method using mass transfer model, but the emphasis was focused on the capillary tube, while the cavitation flow in the transition tube between the capillary and the evaporator was not involved. As a key component between the capillary tube and the evaporator, the internal flow characteristics of transition tube are closely related to the noise characteristics there. In view of the close relationship between pressure distribution and cavitation and noise, as well as the significant advantages of appropriate volume of vapor in suppressing cavitation and noise [8-10], an effective method to suppress capillary cavitation flow and noise is proposed in this paper: via installing bypass capillary on the transition tube, the refrigerant vapor was induced from the downstream to the outlet of the throttle capillary [18]. ANSYS Fluent was used to numerically simulate the throttling cavitation phenomenon of capillary and transition tubes, which verified the feasibility of aerating structure to suppress cavitation. In addition, the cavitation characteristics in the transition tube were investigated. This research is helpful to understand the complicated mechanism of the cavitation process in the capillary and the transition tube. At the same time, it provides an effective method to suppress cavitation and noise. In addition, it also realizes energy saving and noise reduction without increasing the complexity of the system, which is of great significance to suppress flow noise in small refrigeration system.

2. Numerical Model
The basic idea of HEM model is to treat the two-phase fluid as a homogeneous medium with average characteristic and obeying the basic equation of single-phase fluid by reasonably defining the average value of the two-phase mixture. Since cavitation usually occurs in areas where the velocity is relatively high and the pressure is relatively low, the slip velocity between phases is not considered in most cases [19]. For this reason, this paper uses the HEM model to simulate the cavitation characteristics of the two-
phase fluid. In the framework of this model, the vapor phase and the liquid phase are considered to have the same velocity and pressure, and are in a state of local thermal equilibrium.

2.1. Governing equation

The governing equations based on the N-S equation are shown in Equations (1)−(3), including mass conservation equation, momentum conservation equation, and energy conservation equation.

\[
\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m \mathbf{u}_m) = 0
\]

\[
\frac{\partial \left( \rho_m \mathbf{u}_m \right)}{\partial t} + \nabla \cdot \left( \rho_m \mathbf{u}_m \mathbf{u}_m \right) = -\nabla p + \nabla \cdot (\mu_m + \mu_m^T) \nabla \mathbf{u}_m + \rho_m \mathbf{g} + F
\]

\[
\frac{\partial}{\partial t} \left[ \rho_m E_m \right] + \nabla \cdot \left[ (\rho_m E_m + p) \mathbf{u}_m \right] = \nabla \cdot \left[ \left( \lambda_m + \lambda_t \right) \nabla T \right] + h_v \cdot \dot{R}
\]

Where \( \rho \) is the fluid density, \( \mathbf{u} \) is the velocity, \( t \) is the time, \( p \) is the pressure, \( \mu \) is the viscosity, \( F \) is the volume force, \( \lambda \) is the thermal conductivity, \( T \) is the temperature, \( E \) is the energy, \( \lambda_t \) is the turbulent thermal conductivity, \( h_v \) is the latent heat of phase change, and \( \dot{R} \) is the mass source term during phase change. The subscripts \( v \), \( l \), and \( m \) represent vapor phase, liquid phase, and vapor-liquid mixture respectively.

2.2. Cavitation model

The key of using HEM model to simulate the cavitation effect is that the density of the mixture fluid changes with the variation of vapor volume fraction. Typical method is to combine the equation of state model or the transport equation model to close the equations. The advantage of the transport equation model is that it can simulate the influence of the inertial force during bubble growth and movement on the cavitation effect. The expression and correction of the cavitation source term is quite significant. Zhu et al. made a detailed summary of the classical expression of cavitation source term. This paper adopts Schnerr-Sauer models for simulation, due to its good robustness and fast convergence. The vapor phase transfer equation is shown in Equation (4):

\[
\frac{\partial}{\partial t} \left( \alpha \rho_v \right) + \nabla \cdot (\alpha \rho_v \mathbf{u}) = \dot{R}
\]

Where, \( \alpha \) is the vapor volume fraction; \( \dot{R} \) is the nominal mass source term, which can be expressed in a general form, as shown in equation (5):

\[
\dot{R} = \frac{\rho_l \rho_l}{\rho_m} \frac{d \alpha}{dt}
\]

Schnerr and Sauer use Equation (6) to describe the relationship between vapor volume fraction \( \alpha \) and the density of liquid bubbles per unit volume \( n_B \):

\[
\alpha = \frac{4}{3} \frac{n_B \pi R_B^3}{1 + \frac{4}{3} n_B \pi R_B^3}
\]

Where, \( R_B \) is the bubble radius.

According to the classical theory of cavitation dynamics, the Rayleigh Plesset equation is properly simplified and deduced, and the expression of the nominal mass source term \( \dot{R} \) can be obtained, as shown in Equations (7) and (8):

\[
p \leq p_v, \dot{R} = 3 \frac{\rho_v \rho_l}{\rho_m} \alpha (1-\alpha) \left( \frac{3}{1-\alpha} \frac{1}{4 \pi n_B} \right)^\frac{1}{3} \left[ \frac{2}{3} \frac{p_v - p}{\rho_l} \right]^{\frac{1}{3}}
\]
\[ p > p_r, R = \frac{3 \rho_l \rho_\infty}{\rho_m} \alpha (1 - \alpha) \left( \frac{\alpha}{1 - \alpha} \frac{3}{4\pi n_\theta} \right)^{\frac{1}{3}} \sqrt[3]{\frac{2 p - p_\infty}{\rho_l}} \]  

(8)

2.3. Turbulence Model

Based on solving the transport equations of turbulent kinetic energy \( k \) and turbulent energy dissipation rate \( \varepsilon \), the \( k-\varepsilon \) two-equation model is a turbulence model widely used in flow characteristic simulation. Compared with the Standard \( k-\varepsilon \) and RNG \( k-\varepsilon \) models, the advantage of the Realizable \( k-\varepsilon \) model is that it widens the application range, improves the calculation accuracy, and can effectively simulate separated flows, rotating shear flows, and cylindrical jet \(^{24}\). Therefore, the Realizable \( k-\varepsilon \) turbulence model is selected for simulation.

\[
\frac{\partial (\rho k)}{\partial t} + \nabla (\rho ku) = \nabla \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k
\]

(9)

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla (\rho \varepsilon u) = \nabla \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + \rho C_1 S \varepsilon
\]

\[
- \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\rho \varepsilon}} + C_{1c} \frac{\varepsilon}{k} C_{3c} G_b + S_E
\]

(10)

Where \( C_1 = \max \left[ 0.43, \frac{\eta}{\eta + 5} \right] \), \( \eta = \frac{k}{\varepsilon} \), \( S = \sqrt{2S_y S_j} \), \( S_j = \frac{1}{2} \left( \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \) (i, j represent coordinates), model constants \( C_{1c} = 1.44 \), \( C_2 = 1.9 \), \( \sigma_k = 1.0 \), \( \sigma_\varepsilon = 1.2 \).

2.4. Physical model, grid and algorithm

A refrigerator capillary was selected, and its design parameters are shown in Table 1. The schematic of the transition tube is shown in Figure 1.

Table 1 Design parameters of the capillary

| Parameter                        | Value   |
|----------------------------------|---------|
| Capillary inner diameter (m)     | 6e-4    |
| Total capillary length (m)       | 3.9     |
| Inner diameter of transition tube (m) | 6e-3   |
| Condensation temperature (K)     | 327.15  |
| Ambient temperature (K)          | 305.15  |
| Evaporation temperature (K)      | 250.15  |
| Refrigerant                      | R134a   |

Figure 1 Schematic of a transition tube (original model)

In this paper, the commercial simulation software ANSYS Fluent is used to carry out the three-dimensional quasi-steady cavitation simulation. The pressure inlet boundary condition is adopted at the capillary inlet, the pressure outlet boundary condition is adopted at the transition tube outlet, and the standard wall function method is selected at the wall. Coupled algorithm is adopted for pressure-velocity coupling. PRESTO! and QUICK algorithm are selected for pressure and volume fraction. The second-order upwind scheme is selected for momentum equation and turbulence equation. The working fluid is R134a, and the physical parameters are from REFPROP \(^{25}\).
The quadrilateral structured grid was used, and a boundary layer was set near the wall. The total number of grid cells is \(7.8 \times 10^5\), and the wall surface \(y^+\) value is less than 30. In order to verify the grid independence, grid encryption was set in the radial direction. The number of grids after encryption is \(1.18 \times 10^6\), and the difference between the pressure and temperature distribution results and the results before encryption is less than 5%.

2.5 Model verification

The experimental data of Li et al. [26] and the numerical model of Prajapati et al. [27] were used to verify the numerical model in this paper. The computational domain is shown in Figure 2, including capillary tube and transition tube. VOF model was used by Prajapati et al. [27], while the metastable phenomenon was not considered as well. Figure 3 shows the comparison between the calculated pressure distribution in the capillary and the experimental data of Li et al. It can be seen that the model in this paper is consistent with the experimental data of Li et al. and the model predictions of Prajapati et al. as well. In the liquid region, the pressure drop along the capillary length is linear, which is caused by the friction effect. However, with the generation of vapor, the flow in the two-phase region of the capillary accelerates due to a decrease in density. An additional pressure drop is produced in the two-phase region, which is the so-called accelerated pressure drop. As vaporization begins in the capillary, the acceleration pressure drop becomes apparent. The refrigerant R12 is no longer in use due to its high ozone depleting potential. At present, R134a still accounts for a large market share of the most commonly used refrigerant. Therefore, R134a is used as the working medium in subsequent simulations.

3. Analysis of calculation results

This paper adopts the model shown in Figure 1 and takes refrigerant R134a as working fluid. By changing the boundary conditions, numerical simulation is carried out on throttling cavitation process of the refrigerant in the capillary tube and transition tube, with emphasis focused on analyzing flow characteristics in the transition tube. A method to suppress cavitation is proposed and its suppressive effect is analyzed.
3.1. Analysis of cavitation characteristics

According to the cavitation mechanism and bubble dynamics, the main factor affecting the inception of cavitation is the pressure distribution in the throttle, and the degree of cavitation is mainly affected by the pressure distribution downstream of the throttle [1]. The pressure distribution of R134a in the capillary tube is quite the same with R12 in Figure 3 shows. This work focuses on the flow characteristic in the transition tube. Figure 4 shows the pressure and the vapor volume fraction distribution on the axis of the transition tube. It can be seen that, after entering the transition tube, there will be a local minimum pressure, and then the pressure will gradually recover.

Figures 5 and 6 show the contour of vapor volume fraction distribution and velocity distribution in the transition tube, respectively. Near the entrance of the transition tube, due to the sudden expansion of the cross-sectional area of the refrigerant flow, the refrigerant sprays out from the capillary, and some vortex areas with low pressure will be formed in this area, accompanied by a large number of bubbles. The vapor volume fraction of the refrigerant reaches 0.92 at the outlet of the capillary. These bubbles flow downstream with the main flow of liquid phase to the pressure recovery region. Collapsing of a large number of bubbles reduces the volume fraction of vapor phase to 0.73. These collapsed bubbles will produce strong pressure pulsation and cavitation noise, thereby affecting the stability of the equipment.

![Figure 4 Variations of pressure and vapor volume fraction on the axis of the transition tube](image1)

![Figure 5 Contour of local vapor volume fraction in transition tube](image2)
3.2. Study on cavitation suppression methods

When the bubbles collapse, huge energy contained in the bubbles will be released instantaneously in the form of pressure and heat, causing great local pressure impact and local temperature increase \cite{1}. As a result, the vibration of the surrounding fluid occurs and radiates to the air through the solid wall, leading to loudness noise. The existence of throttling pressure drop in refrigeration system makes cavitation inevitable. How to suppress the cavitation effect is very important to promote the development of energy conservation and environmental protection of refrigeration throttling technology.

Due to the close relationship between cavitation and pressure distribution, an effective method to suppress cavitation effect and noise in capillary is proposed in this paper. A transition tube is used to connect between the capillary tube and the inlet tube of the evaporator, and a bypass capillary tube is installed on the transition tube. As shown in Figure 7, the refrigerant vapor from downstream of the transition pipe is introduced to the upstream of the transition tube through the bypass capillary tube, due to the pressure difference, so as to improve the local pressure in the aerating area, and reduce the pressure when the cavitation bubble collapses, which effectively reduce the number of bubble collapsing and then reduce the cavitation noise.

Figures 8 show the contour of the local vapor volume fraction in the transition tube with aerating model, and Figure 9-10 show the variation of pressure and vapor volume fraction on the axis. It can be found that the phenomenon of the large number of refrigerant bubbles collapsing after aerating is effectively suppressed; the pressure increases obviously near the entrance of the transition tube; the volume fraction of the vapor phase on the entire axis is flatter, while in the original model, bubbles will grow, collapse, re-grow, and re-collapse many times.
Figure 8 Contour of local vapor volume fraction with aerating model

Figure 9 Comparison of pressure on the axis of the transition tube

Figure 10 Comparison of the vapor volume fraction on the axis of the transition tube

Figure 11 shows the contour of local axial velocity with aerating model. It can be seen that there is also a vortex near the wall of the transition tube, but its intensity (including velocity and thickness) is obviously enhanced compared with Figure 6. The influence of the interaction between the vortex and the main flow on the throttling cavitation effect needs to be studied in the subsequent unsteady cavitation phenomenon. Further studies on cavitation noise and its suppression will be carried out in the future.
In this paper, a method of suppressing cavitation effect by using aerating structure is proposed. The software Fluent is used to simulate the throttling cavitation phenomenon in the capillary tube and the transition tube. The contour of pressure, velocity, and vapor volume fraction of transition tube are given and the feasibility of suppressing cavitation by aerating structure is confirmed. The conclusions are as follows: compared with the original model, the vapor volume fraction at the outlet of the capillary tube is almost unchanged by using the aerating structure, but the vapor volume fraction of the transition tube is significantly improved. In other words, the application of the aerating structure weakens the cavitation collapsing phenomenon in the transition tube, to achieve the purpose of suppressing cavitation.

Compared with the traditional methods of reducing refrigerant noise by changing the flow pattern, the aerating technology used in this paper suppresses the cavitation effect and then reduces the cavitation noise, without affecting the refrigeration system (such as cooling capacity and power consumption). Meanwhile, it is simple and feasible in the existing refrigerator, so that the noise quality of the whole refrigeration system can be improved, especially in a quiet environment. In addition, the aerating method is also suitable for all systems with throttling injection, which can achieve the purpose of reducing noise.

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