Cavitation performance simulation of turbine meter under different temperature water condition

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Abstract. A cavitation thermodynamics model based on phase change, which is suitable for prediction of cavitation with thermal effects is developed. The cavitation characteristic at different temperature and cavitation number is investigated and analyzed. The initial cavitation of turbine flow meter generally occurs in the blade suction side. With the development of cavitation, the cavitation zone will appear on the front and the back end of the conditioner. In order to avoid the gather of cavitation, the design of the optimizing the blade structure should be adapted, and at the same time, the back pressure should be limited on the installation requirements. Expanding the measurement range and preventing cavitation occurs are the goal of the design and installation. The temperature effects on the cavitation of turbine flow meter is quite obvious and the increase of the temperature will delay the occurrence of cavitation. Pressure difference and the impeller torque will change obviously with the decrease of the cavitation number, which will cause the measurement error of the turbine meter.

1. Introduction

Turbine flow meters have been competing successfully with positive displacement flowmeters in many applications due to the economy of installation, low maintenance costs, weight, size and high flow rates per comparable connection size [1]. The turbine meters can be used to measure various flow rates, operating pressures up to 10,000 pounds per square inch, temperature range of -450° to 1000° F. Cavitation in a turbine flowmeter will take place when the local pressures fall close to or below the vapor pressure of the liquid product. The formation of bubbles and their collapse or local vaporization of product as it passes over the rotor blade surface can cause erratic behavior in the turbine flowmeter and excessive wear due to over speeding. Cavitation usually causes the rotor to speed up at the high flow rate due to the increased flow volume and causes the accuracy curve of the turbine flowmeter to be adversely affected. When turbine flow meters are used to measure high temperature water and cryogenic liquid, the cavitation characteristics in such conditions are different from that of room temperature water. This is caused by thermodynamic effects of cavitation [2].

In high temperature water, the pressures observed inside cavities are substantially lower than the vapor pressure corresponding to the free-stream temperature. The reason for this is that the temperature of the liquid in the immediate vicinity of the liquid-vapor interface is depressed below the free-stream temperature because the latent heat of vaporization must be extracted from the bulk liquid.
Thus, the growth of cavitation is suppressed and the cavity size is smaller than it would be if there were no temperature depression effects present.

Until now, there are a lot of cavitation models that have been developed. And these models can be split into two categories. One is to predict the size and shape of the cavitation bubble. For these analyses, the cavity pressure is taken as known (generally corresponding to the free-stream temperature) and thermodynamic effects are not addressed. The other is to predict the temperature depression for known cavity geometry.

For the predictions of the geometrical effects of the cavitation bubble, Furness and Hutton [3] first consider the deformation of the liquid-vapor interfaces to describe the early stage of reentrant jet formation. After that, a homogeneous two-phase mixture of liquid and vapor method has been developed in modeling the cavitation. Kubota et al. [4] proposed to relate the density evolution to the motion of bubbles in the flow. And the bubble evolution is governed by the Rayleigh-Plesset equation according to the pressure field. Recently, different authors proposed more to consider a transport equation model for the void ratio, with evaporation/condensation source terms to control the mass transfer between the two phases [5,6,7]. As the development of CFD technology, more robust numerical methodology is expected to predict and investigate the thermodynamic cavitation. In the paper, a cavitation model based on phase change is developed, suitable for prediction of cavitation with thermal effects; Building the developed cavitation model into the commercial code by using user subroutine; and the cavitation characteristic of turbine flow meter at different temperatures are analysis using the cavitation model.

2. Cavitation model considering the temperature effect

2.1. Governing equations and phase change modeling

The governing equations of mixture cavitation model are the 3D gas-liquid two-phase compressible Navier–Stokes equations, and are written as following.

Mass conservation equation of the mixture phase:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0$$

Momentum conservation equation of the mixture phase:

$$\frac{\partial (\rho u_j)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = \rho g_i - \frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_i}$$

Transport equation to account for the cavitation dynamics of vapor volume fraction:

$$\frac{\partial \alpha}{\partial t} + \frac{\partial}{\partial x_j}(\alpha \rho u_j) = S$$

Where, $\rho$ is the mixture density of water and vapor.
S is the mass transfer of vapor liquid phase change which is described as:

$$S = m^+ + m^-$$

The former and the latter Represents the process of evaporation and condensation respectively.

As we all known, the phase change is developed in the liquid, the pressure inside the bubble is nearly same as the liquid and the pressure is the same with the vapor pressure of the liquid, so we got the mass transportation between the two phase:

$$\dot{m} = \dot{m}^+ = \dot{m}^- = \left(\frac{2\xi}{2-\xi}\right)\left(\frac{M}{2\pi R}\right)^{\frac{1}{2}} \left(\frac{p_{lv} - p}{\sqrt{T}}\right) A$$
For simplicity, the typical bubble size \( r \) is taken to be the same as the limiting maximum possible bubble size. Then, \( r \) is determined by the balance between aerodynamic drag and surface tension force [5]. Also, the vapor pressure need to be modification, in order to accounts for the turbulence-induced pressure fluctuations.

2.2. Physical properties of medium at different temperature
In the process of numerical simulation of the thermodynamic effect of cavitation, the physical properties of the medium must be considered.

2.2.1. Density of water. The density of water at different temperature can be determined through Tamman state equation [8]:

\[
\rho_i = \frac{p + p_v}{K_i(T + T_0)}
\]

Where, \( P_C = 1944.61 \text{ MPa} \) and \( T_0 = 3837 \text{ K} \) represents pressure constant and temperature constant of water respectively, \( K_i = 472.27 \text{ J/kg -K} \) is a liquid constant of water.

2.2.2. The density of the vapor. According to the research of Saito [9], the density of the vapor could be calculated according to ideal gas state equation:

\[
\rho_v = \frac{P}{RT} = \frac{M}{R T}
\]

Where, \( R_v \) represent the vapor constant, \( R_v = R / M = 461.6 \).

2.2.3. Saturated vapor pressure. The relationship between the saturated vapor pressure and saturated temperature can be expressed by experience formula[9]

\[
p_v = p_k \exp\left\{ (1 - \frac{T_k}{T})(a + (b - cT)(T - d)^2) \right\}
\]

where: \( p_k = 22.130 \text{ MPa}, T_k = 647.31 \text{ K}, a = 7.21379, b = 1.1520 \times 10^{-5}, c = -4.787 \times 10^{-9}, d = 483.16 \).

2.2.4. Other physical properties. Thermal conductivity, specific heat capacity and dynamic viscosity coefficient of water and vapor, the surface tension coefficient of water, etc. must be expressed as a function of temperature through curve fitting, and dynamic update in the process of numerical simulation of when considering the effect of thermodynamic calculating process of cavitation.

3. Comparing Numerical results at different temperature

3.1. The pressure distribution of internal flow field under different temperature
Figure 1 show the pressure distribution on the impeller at different temperature (\( T = 25 \text{ °C}, 70 \text{ °C} \) and \( 100 \text{ °C} \)) and different cavitation number (\( \sigma = 1.0 \) and 0.5). Low pressure area is mainly located at the leading edge on the suction surface of the impeller, and as the increase of the temperature, the pressure increase which means the temperature can delay the occurrence of cavitation.

3.2. Vapor volume fraction at temperature \( T=25 \text{ °C} \) of turbine flowmeter
According to the research results of Okita and Kajishima [10], the vapor volume fraction =10% can be regarded the gas-liquid. The vapor volume fraction may reflect the bubble position and volume change. Figure 2 shows the bubble volume and position at different cavitation number when the temperature at 25°C. When \( \sigma = 2.15 \), the cavitation begin to appear gradually, at this time, the cavitation occurs mainly in the suction side of impeller. It can be seen with the decrease of the cavitation number,
the number and volume of the bubble increase. Further reduce the cavitation number, when \( \sigma = 1.2 \), bubble volume increase, cavitation began to appear on the front end of the front conditioner. When the cavitation number \( \sigma = 0.8 \), the bubble volume is larger, and cavitation can occur in the trailing edge of the impeller.

![Figure 1. Pressure distribution on the impeller at different temperature and cavitation number.](image)

3.3. Temperature effects on the bubble volume fraction of turbine flowmeter

Analysis the vapor volume change at different temperature by 10% vapor volume fraction (figure 3). At the cavitation number \( \sigma = 1.2 \), the cavitation volume decrease, as the temperature increased from 25 \( ^\circ \)C to 100 \( ^\circ \)C and cavitation appeared in the front-end and back-end of the conditioner and the suction side of the impeller. Also we can find the change rule when the cavitation number \( \sigma = 0.5 \), so the high temperature delay the onset of the cavitation inside the turbine flowmeter.

3.4. Effect on differential pressure and torque of the cavitation number in turbine flowmeter

As we know, the measuring accuracy mainly affected through cavitation effect on the impeller torque. Figure 4 and figure 5 give the pressure and torque effect respectively with the change of cavitation number and temperature. Pressure difference and the impeller torque rise slightly with the decrease of cavitation number, which showed that under the condition of the flow rate is constant, if reduce the back pressure of the turbine flow meter, the differential pressure will rise, and the combined torque of
the drive torque and the viscous drag torque will increase, which cause measurement errors. When
cavitation occurs in the turbine meter, the suction side of the impeller became the cavitation area,
cause the viscous friction drag torque decreased.

For the turbine flow meter is not used to doing work of rotary fluid machinery, the design
requirements to minimize disturbance to the flow, so even in smaller cavitation number ($\sigma=0.5$), the
presence of cavitation area on blade suction surface is lesser, also the number of blade is little, so the
cavity do not blocking the flow channel generally, and falling out as the fluid flow downstream.

![Figure 3. Temperature effects on the bubble volume fraction of turbine flowmeter.](image)

![Figure 4. Pressure with cavitation number.](image)

![Figure 5. Impeller torque with cavitation number.](image)

4. **Conclusion**

A cavitation thermodynamics turbulent model based on phase change, which is suitable for prediction
of cavitation with thermal effects is developed. Building the developed cavitation model into the
commercial code by using user subroutine; and the cavitation characteristic of turbine flow meter at
different temperatures are analysis using the cavitation model. The cavitation characteristic at different
temperature and different cavitation number is investigated and analyzed.

1) The cavitation turbulent model considering the temperature effect has been proved to be more
reasonable in simulating the inner cavitation flow filed of the turbine flow meter.
2) The initial cavitation of turbine flow meter generally occur in the blade suction side, with the development of cavitation, the cavitation zone will appear on the front and the back end of the conditioner. In order to avoid the gather of cavitation, the design of optimizing the blade structure should be adapted, and at the same time, the back pressure should be limited on the installation requirements. Expanding the measurement range and preventing cavitation occurs are the goal of the design and installation.

3) The temperature effects on the cavitation of turbine flow meter is quite obvious, the increase of the temperature will delay the occurrence of cavitation. At $T=25$ ℃, the cavitation will occur on the suction side of the impeller at $\sigma=2.15$. But for $T=70$ ℃ and $100$ ℃, the cavitation will occur at $\sigma=1.5$.

4) Pressure difference and the impeller torque will change obviously with the decrease of the cavitation number, which will cause the measurement error of the turbine meter.

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