Numerical simulation of the temperature effects on the performance of rotational supercavitating evaporator

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Abstract. With the application of supercavitation effect, a novel device named Rotational Supercavitating Evaporator (RSCE) has been designed for desalination. In order to study the effect of temperature on the performance of RSCE and then direct the experimental study on RSCE for the next step, numerical simulations are conducted on the supercavitating flows in RSCE under different temperatures and rotational speeds. The results show that the rotational speed, resistance moment and mechanical energy consumed by the rotational cavitator under the critical state with the largest supercavity, decrease with the increase of temperature. And the area and volume of the supercavity increase exponentially with the increase of temperature under the same rotational speed.

1. Introduction

Fresh water deficit has been an increasingly critical global environmental issue, which promotes the development of desalination. The desalination methods can be classified into thermal method and membrane method in line with the different principles. And the current major large-scale industrial desalination methods include multi-stage flash, multiple effect distillation and reverse osmosis. However, the existence of solid walls in multi-stage flash and multiple effect distillation induces the generation of scaling and fouling which would decrease the heat transfer coefficient, and there must be need for rigorous pre-treatment in reverse osmosis. In order to overcome these shortcomings, a novel device named Rotational Supercavitating Evaporator (RSCE) was put forward and designed for desalination based on supercavitation effect [1-3].

Cavitation can be defined as the rupture of a liquid medium by the decrease in pressure under roughly constant temperature. It was originally considered as a harmful phenomenon that must be avoided because of its negative effects, such as wall erosion and the production of noise and vibrations. However, with the development of the researches on the mechanism of cavitation, the positive effects, including drag reduction and cavitating jet, have been applied to engineering practice. In this paper, large energy intensity and heat-mass transfer rate of the steam-water interface in the supercavitation, which is the most intense level of cavitation under low characteristic pressure or large characteristic velocity, are utilized to design RSCE for desalination. Most of the studies on the application of cavitation to desalination are conducted by Russian researchers, and the published relevant literatures...
are scarce. The only example is commercial cavitating desalination device “WATERFALL-1200” designed by the scientific and technical center “TJEROS-MIFI” in Russia [4]. Recently, Likhachev and Li [1-3] put forward RSCE and performed preliminary design and research. The saturation vapor pressure increases with the increase of temperature, thus the rotational speed of RSCE at which the supercavity state is achieved can be lowered with increasing temperature, inducing the reduction of mechanical energy provided for the rotation of RSCE. Therefore, study on the effect of temperature on the performance of RSCE is further conducted in this paper to analyze the energy consumption of RSCE. For cavitating flows, the thermal effects play an important role. Numerical simulation by Kinzel et al. [5] indicated that the thermal effects were important only for specific applications that need high-frequency phenomena, while low-frequency measures needed for loading analysis appeared to be relatively insensitive to thermal effects. Gonçalves and Patella [6, 7] developed a compressible, multiphase and one-fluid solver to study and to predict thermodynamic effects in cavitating flows of cryogens fluids. Numerical simulations were performed for a Venturi geometry with refrigerant R-114 and results were compared with experimental data.

In order to analyze the effects of the temperature on the performance of RSCE, numerical simulations are conducted in this paper on the supercavitating flows in RSCE under different rotational speeds and different temperatures of the water with different saturation pressures. The critical rotational speeds of RSCE at which the supercavity state are achieved under different temperatures are respectively obtained, as well as the change of the supercavity dimension with varying temperature under the same rotational speed. From the perspective of mechanical energy, the variation of the energy consumption of RSCE with temperature is further analyzed, giving the guidance to the experimental study on RSCE for the next step.

2. RSCE model
The core component of RSCE is a rotational cavitator made of two blades with wedge cross section and exit edge of alternative thickness, as shown in Figure 1. According to the size of the experimental device [3], a cylinder with the height of 100mm and the diameter of 430mm is selected as the computational domain. The diameters of the rotational cavitator $d$ and the shaft $d_0$ are 400mm and 52mm, respectively.

![Figure 1. Schematic diagram of the rotational cavitator. (a) three-dimensional schematic diagram, (b) top view.](image)

In order to obtain the blade shape of the rotational cavitator for the first step, the formulae in [3] are herein adopted for calculation. Note that the values of $\alpha$ at different radii in the original method didn’t strictly equal to the wedge angles, i.e. 22.5 degree, at corresponding radii. Moreover, the deviation increases with the decrease of radius $r$. To address this issue, the improved method is proposed and shown in Figure 2, by which the blade shape of the rotational cavitator, shown in Table
1, is obtained through comparing the length of the arc with the length of the supercavity \( L \) which is acquired by the calculation with \( r_c \) instead of \( r \).

**Figure 2.** Schematic diagram of improved calculation method for the blade shape.

### Table 1. Blade shape of the rotational cavitator.

| \( r \) (mm) | \( h \) (mm) | \( r \) (mm) | \( h \) (mm) |
|---|---|---|---|
| 30 | 9.42 | 120 | 4.06 |
| 40 | 8.64 | 130 | 3.78 |
| 50 | 7.80 | 140 | 3.53 |
| 60 | 7.01 | 150 | 3.32 |
| 70 | 6.31 | 160 | 3.13 |
| 80 | 5.70 | 170 | 2.96 |
| 90 | 5.19 | 180 | 2.80 |
| 100 | 4.76 | 190 | 2.66 |
| 110 | 4.38 | 200 | 2.54 |

### 3. Numerical method

#### 3.1. Governing equations

Numerical simulations are conducted on the three-dimensional steady supercavitating flows in this paper. And supercavitating flow is a multiphase and turbulent flow. Mixture model based on the homogeneous equilibrium multiphase flow theory is selected as the multiphase flow model in the numerical simulation, in which the mixture of the gas and liquid phases is considered as homogeneous single-phase fluid. And the equations in this model are shown below.

**Continuity equation of the mixture phase:**

\[
\nabla \cdot (\rho_m \vec{v}_m) = 0
\]

**Momentum equation of the mixture phase:**

\[
\frac{\partial}{\partial t} (\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla \left[ \mu_m \left( \nabla \vec{v}_m + \nabla \vec{v}_m^T \right) \right]
\]

**Transportation equation of the volume fraction of the gas phase:**

\[
\nabla \cdot (\alpha_g \rho_g \vec{v}_m) = R_c - R_e
\]

where \( \rho_m \) is the density of the mixture phase, \( \vec{v}_m \) is the velocity, \( \alpha_g \) is the volume fraction of the gas phase, \( \rho_g \) is the density of the gas phase, \( R_e \) and \( R_c \) are the production rate and condensation rate of the gas phase, respectively. In order to depict \( R_e \) and \( R_c \), Schnerr-Sauer model [8] is adopted as the cavitation model. Turbulent flow in the numerical simulation is described by Realizable \( k - \varepsilon \) model. And the Scalable wall function is adopted to solve the flow near the wall.

#### 3.2. Mesh, boundary conditions and properties

The computational domain is meshed by the structured grids, and the meshes near the blades are arranged to be denser. Both the top and bottom of the computational domain are set to be pressure outlet with the pressure of 101325Pa. The cylindrical surface is set as fixed no-slip wall, and other boundaries are set to be no-slip wall with constant rotational speed. The thermodynamic properties of water and steam under different temperatures are set in line with the international standard for the thermodynamic properties of water and steam IAPWS95 [9].
3.3. Mesh independence verification

In order to guarantee the accuracy and economy of the calculations, the mesh independence is verified in advance. Five sets of mesh with 2084720, 3994000, 6042280, 8566000 and 9700120 grids are successively adopted for numerical simulations under the temperature of 30°C with the rotational speed of 4000r/min. According to the results shown in Figure 3, the resistance moment that acts on the blades \( M_d \) and the volume of the supercavity \( V_c \) nearly remain constant for the meshes with the number of the grids above 8566000. Note that the profile of the supercavity is defined as the isosurface with the vapor volume fraction of 0.5. Therefore, the mesh with 8566000 grids is selected in the following numerical simulations.

![Figure 3. Verification of mesh independence.](image)

4. Results and discussions

Numerical simulations are conducted on the supercavitating flows in RSCE under different rotational speeds and temperatures varied from 20°C to 80°C with increment of 10°C. The critical rotational speeds for different temperatures, at which the supercavitation states are achieved, are firstly obtained, as well as the resistance moments imposed on the blades, resulting in the acquisition of mechanical energy consumed by RSCE. And then the effects of temperature on the performance of RSCE are further studied by numerical simulations under the same rotational speed and different temperatures.

4.1. Results for critical rotational speed

Numerical simulations are performed on the supercavitating flows in RSCE under different temperatures and rotational speeds to obtain the critical rotational speed for each corresponding temperature, at which the largest supercavity is formed in RSCE. And above this critical value, the tail of the supercavity reaches to the next blade, causing the generation of asymmetric supercavities in the simulation. The profile of the supercavity at the critical rotational speed for 30°C is shown in Figure 4. It can be seen that the top view of the supercavity profile is similar to symmetric sectors. Furthermore, re-entrant jet forms at the tail of the supercavities for smaller radii.

Figure 5 depicts the variations of critical rotational speed \( \omega_c \), resistance moment \( M_d \) and mechanical energy \( P_m \) with temperature \( T \). And all decrease with the increase of temperature. As a result of the supercavities with the same dimensions generated by the rotational cavitator, cavitation numbers for different cases at corresponding critical rotational speeds under different temperatures should be the same. Therefore, the square of the critical rotational speed is proportional to the difference between the ambient pressure and saturation vapor pressure based on the definition of
cavitation number, resulting in the decrease of critical rotational speed with the increase of the temperature for the rise of saturation vapor pressure. And then the resistance moment decreases with the reduction of rotational speed. Eventually, the mechanical energy consumed by rotational cavitator decreases because of the reduction of the rotational speed and resistance moment.

![Figure 4. Profile of the supercavity.](image)

**Figure 4.** Profile of the supercavity.

![Graph](image)

**Figure 5.** Variations of critical rotational speed, resistance moment and mechanical energy with temperature.

4.2. Results for the same rotational speed

In order to further study the effect of the temperature on the performance of RSCE, numerical simulations are conducted on the supercavitating flows in RSCE under different temperatures with the same rotational speed. The rotational speed of 3400r/min corresponding to critical rotational speed at 80°C is selected for the numerical simulations in this section based on the results obtained above. The results, including the changes of resistance moment $M_d$, area $A_c$ and volume $V_c$ of supercavity with temperature, are shown in Figure 6. It can be seen that the resistance moments imposed on the rotational cavitator under different temperatures roughly keep unchanged for the constant rotational speed. Both $A_c$ and $V_c$ increase exponentially with the increase of temperature, resulting from the decrease of cavitation number induced by the increase of saturation vapor pressure.

5. Conclusions

Numerical simulations are successively conducted on the supercavitating flows in RSCE for the different temperatures under different rotational speeds and the same rotational speed to study the effect of temperature on the performance of RSCE. The supercavity profile and critical rotational
speed for each temperature are obtained, as well as the variations of resistance moment, mechanical energy, area and volume of supercavity with temperature. The main conclusions are given below.

1. The rotational speed, resistance moment and mechanical energy consumed by the rotational cavitator under the critical state, at which the largest supercavity is generated, decrease with the increase of temperature.

2. The resistance moment is affected by the rotational speed rather than the temperature. The area and volume of the supercavity exponentially increase with the increase of temperature under the same rotational speed.

![Figure 6](image) Variations of resistance moment, area and volume of supercavity with temperature at the same rotational speed.

Acknowledgments
This work is supported by National Natural Science Foundation of China (51276046). The authors would like to appreciate the valuable discussions with the members of Complex Flow and Heat Transfer Lab.

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