Numerical study on the performance of rotational supercavitating evaporator with optimized blade shape

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Abstract. Based on supercavitation effect, a novel device named Rotational Supercavitating Evaporator (RSCE) has been designed for desalination. In order to improve the performance of RSCE, the optimal design of three-dimensional blade shape is performed by utilizing the empirical formulae which have been validated before. Numerical simulation is then conducted on the supercavitating flow in RSCE with the optimized blade, and the supercavity dimension generated by rotational cavitator is obtained, which is further compared with the above-mentioned empirical formulae obtained by two-dimensional calculations. The results show that the supercavity length obtained by numerical simulation on the optimized blade increases with the increase of radius at first, and then decreases at larger radii, which is much smaller than the result of empirical formula at each radius.

1. Introduction

As a global environmental issue, the shortage of fresh water is becoming increasingly severe. And seawater desalination is considered the most promising solution, which promotes the rapid development of desalination technologies. Desalination methods can be classified into thermal method and membrane method in line with different principles. And the current major large-scale industrial desalination methods include multi-stage flash (MSF), multiple effect distillation (MED) and reverse osmosis (RO). However, the existence of solid walls in MSF and MED induces the generation of scaling and fouling which would result in low heat-mass transfer rate, while rigorous pre-treatment is indispensable in RO process for the mitigation of membrane fouling. In order to overcome above-mentioned shortcomings, supercavitation effect is utilized for desalination.

Cavitation is such a phenomenon that a liquid medium is ruptured by the decrease in local pressure under roughly constant temperature, resulting from the vaporization of liquid phase and the abrupt expansion of nuclei inside the liquid into obvious bubbles. Supercavitation is the most intense level of cavitation under low characteristic pressure or large characteristic velocity. Similar to MSF and MED, phase change is involved in the supercavitation-based desalination. However, the occurrence of heat-mass transfer at the steam-water interface in the supercavitation has the advantages of large energy

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intensity and scaling-free [1], that’s why supercavitation effect is taken advantage of for seawater desalination.

Most of the studies on the application of supercavitation to desalination are conducted by Russian researchers. In 1984 Machinski [2, 3] introduced stationary conical supercavitating evaporator into desalination, which has the ability to create a relatively stable supercavity and can be connected to vacuum system for steam extraction. However, the entire system included multiple cascading evaporators, and its industrial application for desalination requires continuous high-volume recirculation of the subcooled hot source water through the system. This scheme is metal-intensive and the ratio of supercavity volume to the water bulk volume is very small, and it also uses energy-intensive pump recirculation system. Combining electromagnetic treatment with supercavitation, scientific and technical center “TJEROS-MIFI” in Russia designed and manufactured commercial cavitating desalination device “WATERFALL-1200” with a productivity of 1200 m$^3$/d [4]. This device consumed electrical energy up to 3 kWh for unit volume of fresh water and ensured more than 99% rejection rate under operation on the source water with TDS (Total Dissolved Solids) up to 65000 mg/L, which was significantly competitive with current major large-scale industrial desalination technologies. Recently, a novel device named Rotational Supercavitating Evaporator (RSCE) was put forward, and preliminary design and research were also performed [1, 3, 5, 6].

The core component of RSCE is a rotational cavitator made of two blades with wedge cross section and alternative thickness of exit edge, which is used for the formation of supercavitation and the production of steam. Therefore, the hydrodynamic characteristic of three-dimensional blade shape is of great importance for the performance of RSCE. In this paper, three-dimensional blades of different sizes are designed based on the empirical formulae of supercavity length which have been obtained by two-dimensional numerical simulations on planar symmetric wedge-shaped cavitators of different wedge angles [7]. The calculation method for the blade shape is also improved for better accuracy. The blade shape of optimal performance is then determined based on several geometrical limitations. Numerical simulation is conducted on the supercavitating flow in RSCE with the optimized blade, and the supercavity dimension generated by rotational cavitator is obtained. The supercavity lengths at different radii are also compared with the above-mentioned empirical formulae obtained by two-dimensional calculations.

2. Design and modelling of RSCE with optimized blade shape

All of the empirical formulae of supercavity length as a function of cavitation number have been validated by existing experimental results [7], based on which the blade shape of RSCE can be obtained for each certain wedge angle and rotational speed. Practically, the three-dimensional blade shape is determined by the fixed wedge angles and alternative thicknesses of the exit edge at different radii, and the thickness of the exit edge is determined by the comparison between the supercavity length and arc length at the corresponding radius. Detailed algorithm for the thickness of the exit edge was illustrated in [5].

However, the values of $\alpha$ at different radii in the original calculation method for blade shape didn’t strictly equal to the desired wedge angles at corresponding radii. Moreover, the deviation would increase with the decrease of radius $r$. To address this issue, the improved method is proposed and shown in Figure 1, in which the length of the supercavity $L$ is obtained by the calculation with $r_c$ instead of $r$. According to the calculation method, there exists a corresponding blade shape for each certain wedge angle and rotational speed as mentioned above. Due to the space limitation and the same qualitative trend, only the variations of half-thickness of the exit edge $h$ with the radius $r$ for different wedge angles at the rotational speed of 5000 r/min and for different rotational speeds at the wedge angle of 45$^\circ$ are extracted for analysis and shown in Figure 2, while the detailed results for other wedge angles and rotational speeds are not provided. It can be obtained from Figure 2 that the half-thickness of the exit edge decreases with the increase of radius for each blade shape. The difference between the half-thicknesses of the exit edge at the blade root and at the blade tip increases with increasing wedge angle for the same rotational speed (Figure 2(a)), thus the blade shape with
smaller wedge angle is more suitable for the considerations of the size of the shaft (due to the need of larger shaft length for a certain shaft diameter or larger shaft diameter for a certain shaft length at larger wedge angles) and the blade length (because of the requirement for mechanical strength at larger radius where half-thickness of the exit edge is too small). Besides, half-thickness of the exit edge for each radius decreases with the increase of rotational speed at the same wedge angle (Figure 2(b)), hence the blade shape designed for higher rotational speed is selected on account of the sizes of shaft and blade. With more consideration of blade’s mechanical strength, the limitation of \( h = 1 \) mm, i.e., the thickness of the exit edge of 2 mm, is set in the design for blade shape. Ultimately, the optimized blade with wedge angle of 45º and design rotational speed of 5000 r/min is designed, whose three-dimensional model is schematically shown in Figure 3. And its detailed parameters of blade shape are tabulated in Table 1. The shaft diameter \( d_0 \) and diameter \( d \) of this blade are 70 mm and 200 mm, respectively.

![Figure 1](image1.png)

**Figure 1.** Schematic diagram of improved calculation method for the blade shape.

| \( r \) (mm) | \( h \) (mm) | \( r \) (mm) | \( h \) (mm) |
|-------------|-------------|-------------|-------------|
| 35          | 9.89        | 70          | 2.72        |
| 40          | 8.63        | 75          | 2.25        |
| 45          | 7.33        | 80          | 1.88        |
| 50          | 6.09        | 85          | 1.58        |
| 55          | 4.98        | 90          | 1.34        |
| 60          | 4.06        | 95          | 1.15        |
| 65          | 3.31        | 100         | 0.99        |

**Table 1.** Half-thicknesses of the exit edge (\( h \) in Figure 1) at different radii for the optimized blade with wedge angle of 45º and design rotational speed of 5000 r/min.

![Figure 2](image2.png)

**Figure 2.** Variations of half-thickness of the exit edge \( h \) with the radius \( r \) for (a) different wedge angles at the rotational speed of 5000 r/min and for (b) different rotational speeds at the wedge angle of 45º.

3. **Numerical simulation on RSCE with optimized blade shape**

3.1. **Numerical method**

Numerical simulation is conducted on the three-dimensional steady supercavitating flow in this paper. And supercavitating flow is a multiphase and turbulent flow. Therefore, multiphase flow and turbulence models should be adopted in the numerical simulations. Herein, Mixture model based on
the homogeneous equilibrium multiphase flow theory is selected as the multiphase flow model, in which the mixture of the gas and liquid phases is considered as homogeneous single-phase fluid. And

![Figure 3. Schematic diagram of the optimized blade. (a) three-dimensional schematic diagram, (b) top view.](image)

the equations in this model are shown below.

Continuity equation of the mixture phase:

$$\frac{\partial}{\partial x_i} (\rho_m u_i) = 0$$  \hspace{1cm} (1)

Momentum equation of the mixture phase:

$$\frac{\partial}{\partial x_j} \left[ \rho_m u_j \right] = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \left( \mu_m + \mu_t \right) \left( \frac{\partial u_j}{\partial x_j} + \frac{\partial u_i}{\partial x_i} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right) \right]$$  \hspace{1cm} (2)

Transportation equation of the volume fraction of the gas phase:

$$\frac{\partial}{\partial x_i} \left( \alpha_v \rho_v u_i \right) = R_e - R_c$$  \hspace{1cm} (3)

where \( u_i \) or \( u_j \) is the velocity of mixture phase, \( p \) is the pressure, \( \mu_t \) is the turbulent viscosity, \( \alpha_v \) is the volume fraction of the gas phase, \( \rho \) and \( \mu \) are the density and viscosity, respectively; subscripts \( m \) and \( v \) represent mixture and vapor phases, respectively. The thermodynamic properties of liquid water and vapor are set in line with the international standard for the thermodynamic properties of water and steam IAPWS95 [8] at 25°C: \( \rho_l = 997.00 \, \text{kg/m}^3 \), \( \mu_l = 8.9011 \times 10^{-4} \, \text{Pa} \cdot \text{s} \), \( \rho_v = 0.023075 \, \text{kg/m}^3 \), \( \mu_v = 9.8669 \times 10^{-6} \, \text{Pa} \cdot \text{s} \). Herein, the subscript \( l \) represents liquid phase. The density and viscosity of mixture phase are defined as \( \rho_m = \alpha_v \rho_v + (1-\alpha_v) \rho_l \) and \( \mu_m = \alpha_v \mu_v + (1-\alpha_v) \mu_l \). \( R_e \) 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 [9] is adopted as the cavitation model. Turbulent flow in the numerical simulation is described by \( k-\varepsilon - v^2 - f \) (V2F) turbulence model, which has been verified for simulating cavitating flows [7]. V2F model is an extension of \( k-\varepsilon \) model and includes two additional equations to represent the turbulence anisotropy without damping functions. This turbulence model was proposed by Durbin [10] and several versions have been put forward to improve this model for the enhancement of numerical stability. The adopted version in this paper is derived from the code-friendly one introduced by Lien and Kalitzin [11], and detailed equations are not given due to space limitation.
A cylinder with the height of 100mm and the diameter of 430mm is selected as the computational domain, as shown in Figure 3, as well as the settings of coordinate system in the simulations. The computational domain is meshed by unstructured grids with denser prismatic meshes gathering in the boundary layer around the blades and tetrahedral meshes in the rest space. Both the top and bottom of the computational domain are set to be pressure outlet with the pressure of 101325 Pa. The cylindrical surface is set as fixed no-slip wall, and other boundaries are set to be no-slip wall with constant rotational speed.

3.2. Results and discussions

Numerical simulation is conducted on the supercavitating flow around optimized blade in RSCE at rotational speed of 5000 r/min. The profile of the supercavity is shown in Figure 4, which is defined as the isoline with $\alpha = 0.1$ [7]. It can be seen that the supercavity profile is centrosymmetric about the axis. Moreover, re-entrant jet generates at the tail of the supercavity for smaller radii, which can be captured by the depression of the profile. For more intuitive observation, Figure 5 depicts the flow field in the cylindrical surface with the radius of 0.04 m, in which the red line represents the supercavity profile. It can be seen that a jet with larger velocity and the direction towards upstream forms right behind the supercavity, inducing the depression of profile.

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

However, the supercavity does not take up most of the space between two blades as expected. The disparity between empirical formula and three-dimensional numerical simulation result is shown in Figure 6. The difference is to a larger extent, which increases with the increase of radius, especially for the larger radii, where supercavity length decreases with increasing radius for three-dimensional numerical simulation result. This significant difference is resulted from the fact that empirical formulae were obtained by numerical simulations on two-dimensional planar cavitating flows around wedge-shaped cavitators with no consideration for the effect of rotation, indicating that empirical formulae for supercavity length should be modified, which can be realized by theoretical derivation or
three-dimensional numerical simulation on the blade with constant thickness of the exit edge. Besides, the event that supercavity length decreases with increasing radius at larger radii for numerical simulation result can be possibly explained by tip vortex which has been observed in the experiments on RSCE [3].

![Figure 6](image)

**Figure 6.** Variation of supercavity length $L$ with the radius $r$ for numerical simulation result and comparison with the result of empirical formula.

4. Conclusions
Optimal design for the blade shape of RSCE is performed by utilizing empirical formulae of supercavity length and improving the calculation method for blade shape. Optimized blade is then determined by several geometrical limitations and mechanical strength. Numerical simulation is conducted on the optimized blade, and the supercavity lengths at different radii are obtained and compared with the result of empirical formulae. The main conclusions are given below.

The blade with wedge angle of 45° and design rotational speed of 5000 r/min is picked out as the optimized blade. The supercavity length obtained by numerical simulation on the optimized blade increases with the increase of radius at first, and then decreases at larger radii, which is much smaller than the result of empirical formula at each radius. And the empirical formulae of supercavity length would be modified in the future research.

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