# Numerical study on thermodynamic characteristics of rotational supercavitating evaporator

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**Abstract.** Rotational Supercavitating Evaporator (RSCE) has been proposed as a new technology for seawater desalination. However, thermodynamic characteristics of rotational supercavitation are still vacant. In this paper, numerical simulations are conducted on the supercavitating flows around a 3D rotating blade of RSCE with different rotational speeds and extraction pressures. Energy effect is taken into consideration in the simulation and thermodynamic characteristics of rotational supercavitation are obtained. Rotational supercavitation has a larger convective heat transfer coefficient than the boiling on a heated wall.

## 1. Introduction
Water is the source of our lives and the material basis of the human beings' survival. There exists a severe shortage of fresh water around the world, which has led to development of seawater desalination methods. The most widely used technologies are thermal methods and membrane methods, which make up about 95% of worldwide fresh water production. However, the former is limited by the scale formation and heat transfer coefficient, and the later is limited by the membrane fouling and the recovery factor. There is a technological bottleneck in the thermal methods to evaporate water into steam free from scale formation and dramatical increase in heat transfer coefficient. On the surface of supercavity, water evaporates into steam in the same way with boiling of water. However, the heat transfer coefficient of evaporation from the surface of supercavity depends on the heat-flux density and there is no scale formation. So a device named Rotational Supercavitating Evaporator (RSCE) was put forward for desalination based on supercavitation effect. The RSCE model is shown in Figure 1. When the rotational blade rotates at high speed (1000~5000 r/min), supercavitation is generated right behind the blade and the steam is extracted from the inside of supercavity, which would be then condensed to produce fresh water. The RSCE also has a good application foreground in sewage disposal, such as nuclear waste water and polluted water containing heavy metals.
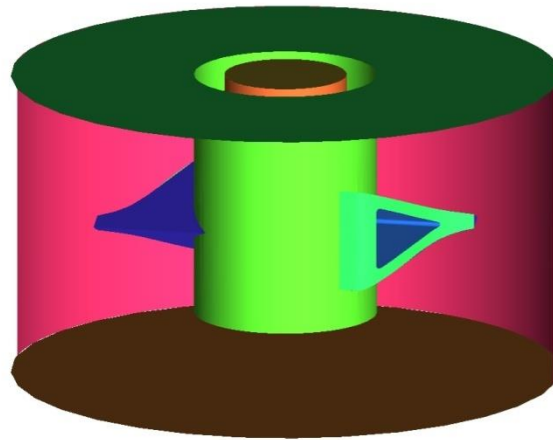
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Figure 1. 3D RSCE model

Cavitation can be defined as the breakdown of a liquid medium under very low pressures and applied to cases in which the liquid is either static or in motion. It was first discovered on the propeller in the warship of British Royal Navy in 1897. The study on cavitation primarily focused on the prevention of negative influence of cavitation phenomenon such as noise, vibration and surface erosion. Subsequently the drag reduction effect of supercavitation on an underwater body was found, and it came an upsurge of research on the drag reduction of underwater vehicle based on supercavitation effect. 30 years ago, Machinski [1] introduced the stationary supercavitating cone evaporator, which can be connected to vacuum system for steam extraction for desalination. Recently Likhachev and Li [2-4] put forward RSCE and performed preliminary design and research. Li and Zheng acquired many characteristics on supercavitation of 2D wedge-shaped cavitators and 3D rotational cavitators [3-6]. Even though many characteristics of rotational supercavitation are acquired, the thermal effect on the steam extraction process has never been taken into account. So detailed thermodynamic characteristics of rotational supercavitation, for example, convective heat transfer coefficient, are still vacant.

In order to obtain thermodynamic characteristics of rotational supercavitation, numerical simulations are conducted on 3D RSCE model shown in Figure 1. Energy effect is taken into consideration in numerical simulations to investigate the thermal characteristics of rotational supercavitation. Numerical simulations are performed under different steam extraction pressures to investigate the thermodynamic characteristics of rotational supercavitation with different quantities of steam extraction. As a conclusion, the thermodynamic characteristics of rotational supercavitation are summed up.

## 2. Numerical method

### 2.1. Governing equations
Numerical simulations are conducted on the three-dimensional steady supercavitating flows in this paper. In the numerical simulation, supercavitating flow is a multiphase and turbulent flow and mixture model based on the homogeneous equilibrium multiphase flow theory is selected as the multiphase flow model. 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:

$$\nabla \cdot \left( \rho_m \vec{v}_m \right) = 0 \tag{1}$$

Momentum equation of the mixture phase:

$$\frac{\partial}{\partial t}\left(\rho_m \vec{v}_m\right) + \nabla \cdot \left(\rho_m \vec{v}_m \vec{v}_m\right) = -\nabla p + \nabla \cdot \left[\mu_m\left(\nabla \vec{v}_m + \nabla \vec{v}_m^T\right)\right] \tag{2}$$

Transportation equation of the vapour fraction of the gas phase:

$$\nabla \cdot \left(\alpha_v \rho_v \vec{v}_m\right) = R_e - R_c \tag{3}$$

where $\rho_m$ is the density of the mixture phase, $\vec{v}_m$ is velocity, $\alpha_v$ is the vapour fraction of the gaseous phase, $\rho_v$ is the density of the gaseous phase, $R_e$ are $R_c$ the production rate and condensation rate of the gaseous phase, respectively. In order to depict $R_e$ and $R_c$, Schnerr-Sauer model [7] is adopted as the cavitation model.

For $p_v \geq p$,
$$R_e = \frac{\rho_v \rho_l}{\rho_m} \alpha_v (1-\alpha_v) \frac{3}{\Re_B} \sqrt{\frac{2}{3}\frac{\left(p_v - p\right)}{\rho_l}} \tag{4}$$

For $p_v \leq p$,
$$R_c = \frac{\rho_v \rho_l}{\rho_m} \alpha_v (1-\alpha_v) \frac{3}{\Re_B} \sqrt{\frac{2}{3}\frac{\left(p - p_v\right)}{\rho_l}} \tag{5}$$

where $\rho_l$ is the density of the liquid phase, $p_v$ is the saturation vapor pressure, $\Re_B$ is the radius of the bubble and defined as follows.

$$\Re_B = \left(\frac{\alpha_v}{1-\alpha_v}\frac{3}{4\pi}\frac{1}{n}\right)^{\frac{1}{3}} \tag{6}$$

Herein, $n$ is the number of the microbubbles within the liquid of unit volume and set as $1 \times 10^{13}$. The energy equation for the mixture multiphase model takes the following form:

$$\frac{\partial}{\partial t}\sum_{k=1}^{n}\left(a_k \rho_k E_k\right) + \nabla \cdot \sum_{k=1}^{n}\left(a_k \vec{v}_k\left(\rho_k E_k + p\right)\right) = \nabla \cdot \left(k_{eff}\nabla T\right) + S_E \tag{7}$$

where $k_{eff}$ is the effective conductivity. The first term on the right-hand side represents energy transfer due to conduction. $S_E$ includes any other volumetric heat sources.
where:

$$E_k = h_k - \frac{p}{\rho_k} + \frac{v_k^2}{2} \tag{8}$$

Turbulent flow in the numerical simulation is described by Realizable $k - \varepsilon$ model and Scalable wall function is adopted to solve the flow near the wall.

*2.2. Boundary conditions and mesh*
The computational domain is shown in Figure 2. It is a cylinder-shape domain with the rotational blade fixed on the top surface. The diameter of the cylinder-shape domain is 200 mm and the height is 100 mm. The maximum diameter of the rotational blade is 120 mm and the diameter of the rotational axle is 60 mm. The diameter of the extraction tunnel is 40 mm.

The annular region on the top surface is set as velocity-inlet and two fluid velocities, 1m/s and 3m/s, are used in the numerical simulation in different cases. The temperature of the water flowing into RSCE from the inlet is set as 379.15K. So, the hot water, flowing into RSCE from the top surface,

release the heat through the evaporation on the surface of supercavity and flow out from the bottom surface as cooled water. The bottom surface is set as pressure outlet with the pressure of 134010 Pa, which is the saturated vapor pressure at 381.15 K. In this case, the water entering from the inlet has a very small supercooling degree of 2 K, which contributes to the generation of supercavity. The exit of the extraction tunnel is set as pressure outlet with the same pressure as the extraction pressure of RSCE. In the simulation, three extraction pressure, 84608 Pa、70182 Pa and 47414 Pa, are adopted, respectively. The side surface of the cylinder-shaped domain,  the blade and the  rotational axle are set as walls.

The thermodynamic properties of water and steam are defined according to international standard for the thermodynamic properties of water and steam IAPWS95 [8] at 379.15 K. Density of water liquid is $954 \, \text{kg}/\text{m}^3$ , viscosity of water liquid is $2.65 \times 10^{-4} \, \text{Pa} \cdot \text{s}$ , density of water vapor is $0.728 \, \text{kg}/\text{m}^3$ and viscosity of water vapor is $1.25 \times 10^{-5} \, \text{Pa} \cdot \text{s}$ . The computational domain is meshed by the unstructured grids, which is shown in Figure 3.
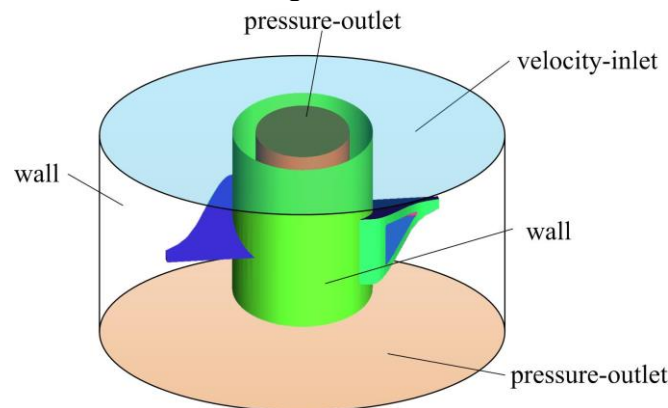


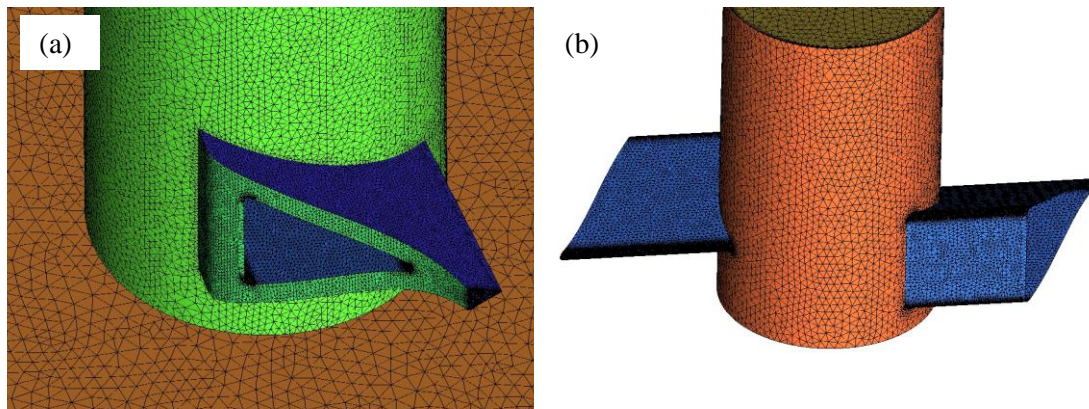**Figure 2.** Schematic diagram of the computational domain.



**Figure 3.** Schematic diagram of the mesh. (a) enlarged part around rotating cavitator, (b) meshes in the extraction tunnel.

## 3. Results and discussions

In the simulation, saturated vapor pressure varies with temperature. As vapor pressure is one of the key parameters that has a vital influence on the supercavitation, it should be fitted with temperature. The fitting function in the simulation of this paper is as follow:

$$P_v = \begin{cases} 519.17 + 10T & 0\text{K} < T \le 301.15\text{K} \\ 7963307 - 109393T + 563.6T^2 - 1.294T^3 + 0.00112T^4 & 301.15\text{K} < T \le 395.15\text{K} \\ 170734.37 + 58T & 395.15\text{K} < T \le 10000\text{K} \end{cases} \quad (9)$$

When the simulation is convergent, the temperature is within the range $301.15\text{K}<T\le395.15\text{K}$, so the fitting function beyond the range is just used to avoid the divergence in the begin of the simulation.

In order to generate supercavity with appropriate size, two rotational speeds of the blade, 2500 r/min and 3000 r/min, are chosen in the simulations. Numerical simulations on RSCE model are conducted with certain rotational speeds and extraction pressures. The hydraulic and thermodynamic characteristics of supercavity formed by blade with different rotational speeds and extraction pressures are obtained.

### 3.1. hydraulic characteristics

In the numerical simulation, two rotational speeds of the blade, 2500 r/min and 3000 r/min, are chosen and three cases with the extraction pressure of 84608 Pa、70182 Pa and 47414 Pa are simulated for each rotational speed. All these cases with the velocity of 1 m/s at the inlet. The supercavitygenerated by the rotational blade is shown in Figure 4 (for 2500 r/min and 84608 Pa). Contours of vapor volume fraction in each case are shown in Figure 5. The contour is on the rotating plane  with the leading edge of the blade on(z=0 plane).
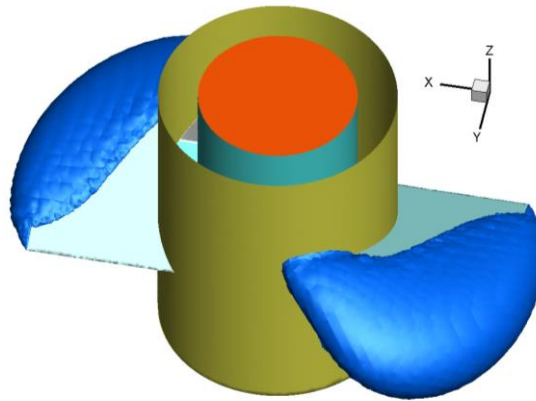


**Figure 4.** Supercavity generated by the rotating blade (for 2500 r/min and 84608 Pa).
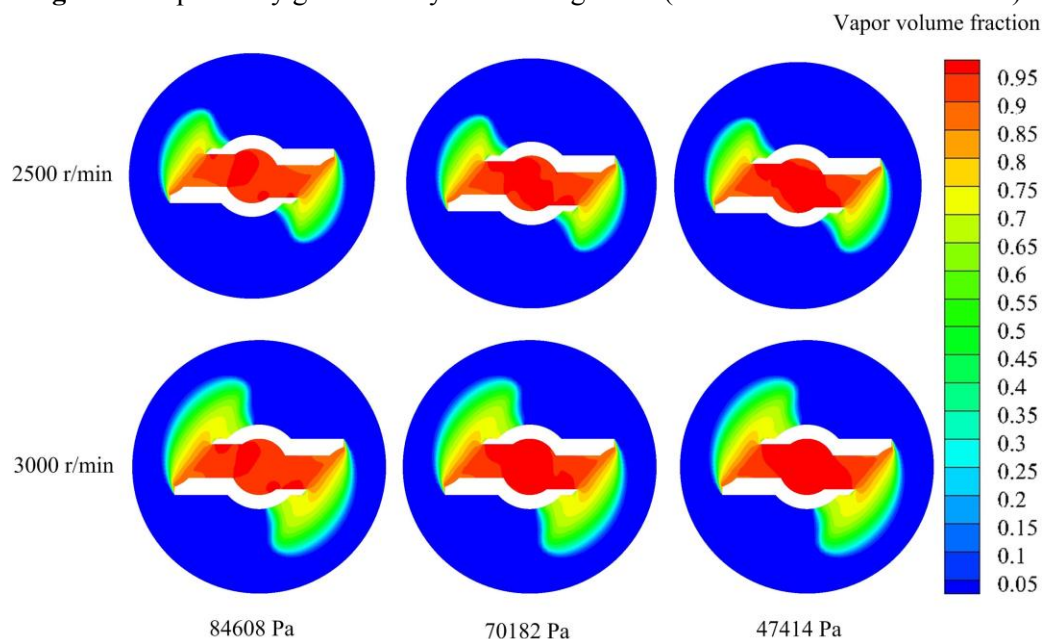


**Figure 5.** Contours of vapor volume fraction in cases with different rotational speeds and extraction pressures.

As observed, the supercavity is just generated right behind two blades and symmetric about the axle. The blade with a higher rotating speed can generate a larger supercavity, and the shape of the surpercavity is not affected by the extraction pressure at the same rotational speed.

Numerical simulation is also conducted with the inlet velocity of 3m/s, in which the rotational speed is 3000 r/min and the extraction pressure is 47414 Pa. Comparing with the case with the velocity of 1 m/s which is shown in Figure 6, it can be obtained that a higher velocity of the flow that strikes on the side surface of supercavity, more visible the effect on the shape of the supercavity. But both the striking velocities of 1 m/s and 3 m/s induce no prominent change of the supercavity shape, which means the effect of smaller velocity on the side surface is acceptable.
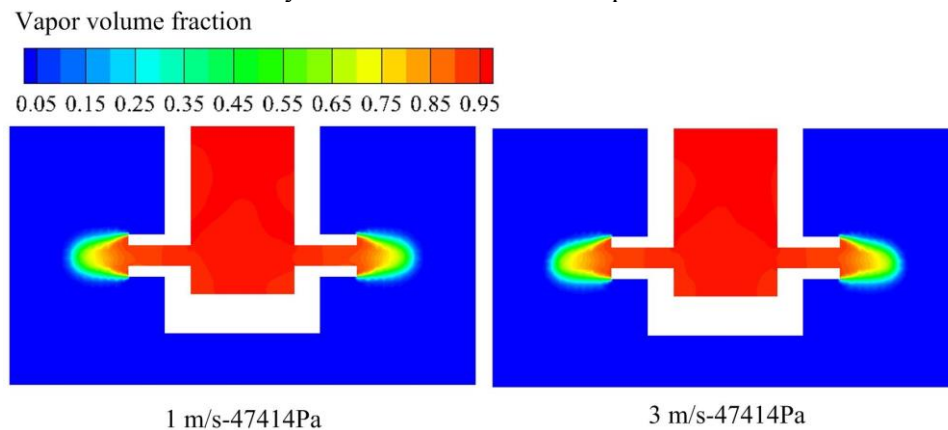


**Figure 6.** Contours of vapor volume fraction in cases with different inlet velocities (plane y = 0).

### 3.2. Thermodynamic characteristics

The temperature distribution is shown in Figure 7 (a). As observed, when flowing through the supercavity area, the hot water is subjected to a significant temperature decline. But the low temperature area beneath rotational axle is abnormal, which is caused by the backflow from the bottom surface, as shown in Figure 7 (b).
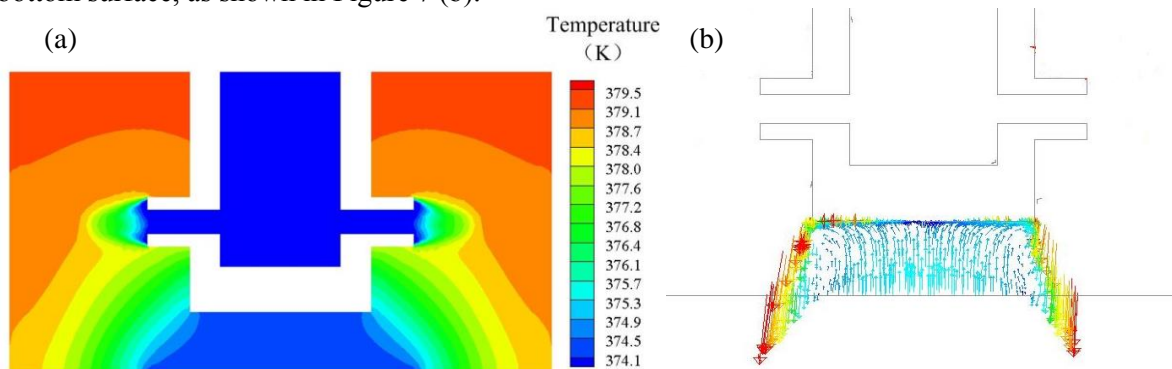


**Figure 7.** Distribution of temperature (plane y=0). (a) contour of temperature in cases with different inlet velocities (plane y=0). (b) velocity vector in partial area which is coloured by temperature.

As the analysis of the result, convective heat transfer coefficient is calculated as follow:

$$h = \frac{\Phi}{A \cdot \Delta T} \tag{10}$$

where heat flux $\Phi$ is calculated from the steam extraction and enthalpy difference between liquid water and vapor. As the area of the supercavity is unobtainable, the area $A$ in the equation is the area of the annular inlet, which is equal to the rotational plane's area of the blade and supercavity. The temperature different $\Delta T$ is calculated from the temperature of the inlet and the boiling temperature of water under the extraction pressure. Thermodynamic parameters are shown in Table 1. The

convictive heat transfer coefficient is much higher than that of the boiling on a heated wall, which means supercavitation has a great enhancement on heat transfer during the evaporation. As observed, a low extraction pressure can generate a high steam extraction and convective heat transfer coefficient, but a higher rotational speed has no contribution to the steam extraction and convective heat transfer coefficient, even it could lead to a larger supercavity.

**Table 1.** Thermodynamic parameters of the RSCE

| Rotating speed (r/min) | Inlet velocity (m/s) | Extracting pressure (Pa) | Steam extraction (kg/s) | Convective heat transfer coefficient (W/(m²· K)) |
|---|---|---|---|---|
| 2500 | 1 | 84608 | 0.00546 | 39149 |
|  | 1 | 70182 | 0.01199 | 59059 |
|  | 1 | 47414 | 0.03336 | 101147 |
| 3000 | 1 | 84608 | 0.00413 | 29598 |
|  | 1 | 70182 | 0.01230 | 60603 |
|  | 1 | 47414 | 0.03279 | 99428 |
|  | 3 | 47414 | 0.03391 | 102840 |

## 4. Conclusions

Numerical simulations are conducted on the cavitating flows around the 3D rotating cavitators with different rotational speeds and extraction pressures. In the simulation, energy effect is taken into consideration and thermodynamic characteristics of rotational supercavitation are obtained.

Blade with a higher rotational speed can generate a larger supercavity and extraction pressure affects the shape of the supercavity little. The flow with smaller velocity of that strikes on the side surface dose not affect the supercavity fatally. The convective heat transfer coefficient of supercavitation is much higher than that of the boiling on a heated wall. Extraction pressure has a significant influence on the steam extraction and convective heat transfer coefficient, while rotating speed does not.

## Acknowledgments

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