Re-entrant Gas Flows of High-speed Ventilated Supercavity

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Abstract

Re-entrant jet closure mechanism usually occurs for ventilated supercavitating flows at high speed in unbounded flows. The tail closure pattern is closely related to gas-leakage mechanism. The multi-fluid model, which involves interphase momentum and mass interactions, is applied to simulate the flows. Re-entrant flow mechanism is analyzed with more detail, and gas velocity distribution laws are presented in the re-entrant flow region. It is also found that maximum gas velocity occurs in the region. The maximum value is much greater than the incoming flow velocity in the opposite direction, and the relationship between the two is illustrated. This study contributes to deeply understand the gas entrainment and closure mechanism of high-speed supercavity.

Keywords: ventilated supercavitating flows; re-entrant flows; velocity distribution

Introduction

Supercavitation drag reduction has a revolutionary impact on the research and development of high-speed underwater vehicle and receives worldwide attentions. A better understanding of supercavitating flow mechanism leads to apply this method and technology quite flexibly. The flows involve many problems, such as phase change, re-entrant jets, gas loss, and these phenomena are interrelated and intricate. As an important part of flow mechanisms, flow structure inside supercavity has been an emergent task to study.

Since ventilated supercavitation was discovered, researchers have made endeavours in this area and some achievements in the formation, hydrodynamics and stability of supercavity[1-5], but inner flow structures remain little focused. Unlike natural case, where vapor-water mixture interacts[6], there are gas vortex ring structures inside ventilated supercavity[7,8]. It is inextricably linked with gas loss[9,10], which not only determines supercavity tail closure[11], but also is crucial to the flow stability and control[12,13].

The multi-fluid model, involving momentum interactions and mass transport between gas, vapor and water, is applied to reveal re-entrant gas flows in the tail region for high-speed supercavitating flows. The re-entrant mechanism is demonstrated by analyzing flow structure in more detail. The velocity distribution laws are presented in the re-entrant regions at different Reynolds and cavitation numbers, and the maximum gas velocity is found and the relationship between the velocity and cavitation number is obtained.

Multiphase flow model

Considering momentum interactions in different phases, the gas-water two-fluid model is qualified for ventilated supercavitating flows[14-16]. However, some unsteady factors or processes can induce natural cavitation in high-speed states. Further considering the vapor-water mass transport, the gas-vapor-water multi-fluid model was developed in our recent work[8] and is applied here. In the model, governing equations consist of the continuity and momentum equations of each phase and the volume conservation and pressure constraint equations. SST model (shear stress transport) based on $k-\omega$ [17] is used to close Reynolds equations. The cavitation model deduced from Rayleigh-Plesset equation[18], which represents the vaporization and condensation processes, is added in vapor and water continuity equations.

Results and discussion

Based on the multi-fluid model, supercavitating flows are simulated to reveal gas flows in the re-entrant flow region defined from sections S_{t1} to S_{t4} in Figure 1, where S_{t1} is the cavity section where re-entrant flows start to

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occur; S_{t4} is the section where the pressure difference between S_{t3} and S_{t4} does not exceed 5%; $\overline{V}$ is the non-dimensional gas velocity, $\overline{V} = V_g/V_\infty$, V_g and γ_g are the gas velocity and volume fraction; V_∞ is the inflow velocity. It can be clearly shown that gas escapes along cavity wall and that most gas flows back into cavity interior. There is a strong adverse pressure gradient, as shown in Figure 2, where $\overline{x}$, $\overline{r}$ and $\overline{p}$ are the non-dimensional axial and radial coordinates and pressure, $\overline{x} = x/L_c$, $\overline{r} = r/r_m$ and $\overline{p} = p/p_f$, L_c is the supercavity length, r_m is the cavity radius, p_f is the ambient pressure. Because the pressure gradient ($-\partial p/\partial x$) is large along the re-entrant flow direction in the beginning, pressure decreases and velocity continues to increase from sections S_{t1} to S_{t3}. Gas speed achieves its maximum in section S_{t3} and is about 1.86 times as large as the inflow speed. Then the pressure gradient is greatly reduced, while the effect of viscous force is significant to decrease the speed. The radial pressure distribution in the cavity section is almost uniform in Figure 2(c), which is consistent with the expansion principle of cavity section[19,20].

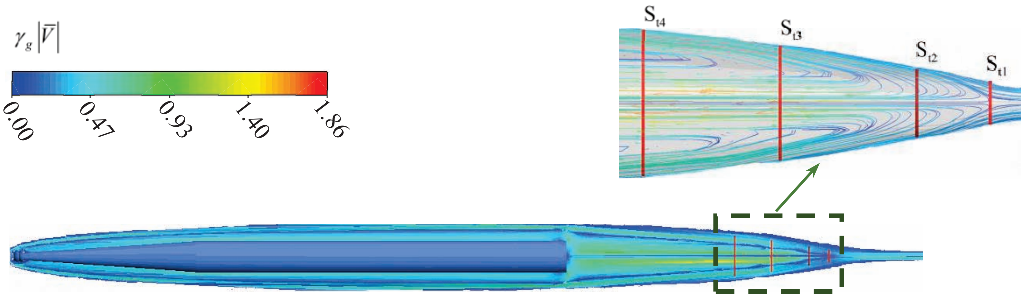

Figure 1 Ventilated supercavitating flows ($Re = 5.20\times10^5$, $\sigma_c = 0.0233$)

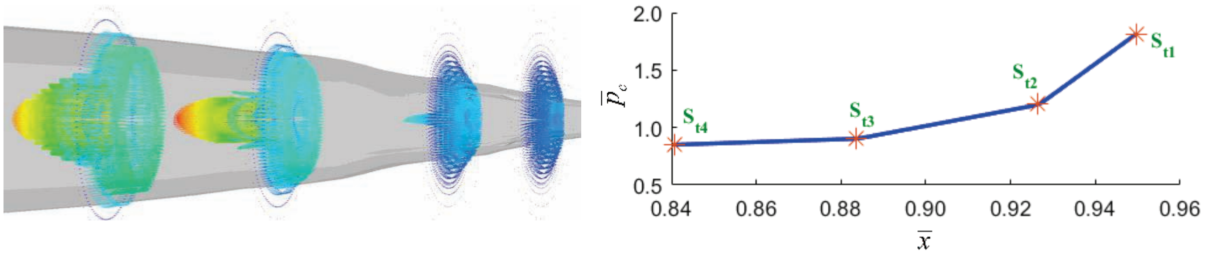

Figure 2(a) Gas velocity distribution

Figure 2(b) Axial pressure distribution

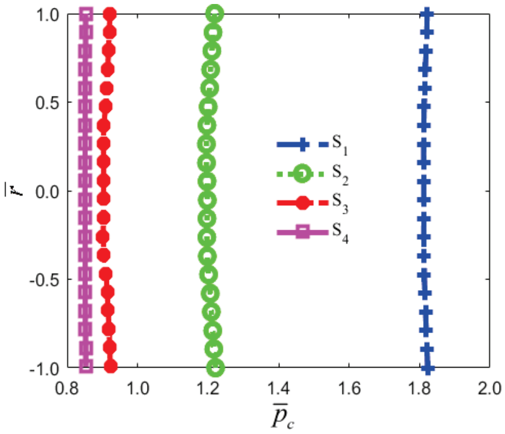

Figure 2(c) Radial pressure distribution

Figure 2 Re-entrant flows under adverse pressure gradient ($Re = 5.20\times10^5$, $\sigma_c = 0.0233$)

Flows simulations are carried out to at different Reynolds and cavitation numbers, and the gas velocity distribution laws are obtained by the analyses of flows in the characteristic sections S_{t1} and S_{t3}. In Figure 3(a), gravity effects are obvious to float supercavity tail, where a group of Froude numbers, Fr = [258.29, 413.26, 628.12], corresponds to different Reynolds numbers; the smaller $\sigma_c F_r$, the greater gravity effect and the more velocity symmetry axis moves up; Cavitation number decreases to increase the pressure in the section S_{t1} so that gas in the central area of the section is entrained away more difficultly and the velocity distribution curves become smoother. The maximum velocity $\bar{V}_m$, $\bar{V}_m = V_m/V_\infty$, always occurs in the re-entrant flow region, as shown in Figure 3(b). It can be seen from Figure 4 that there is a multiple relationship between the maximum and inflow speeds. The smaller cavitation number, the greater the maximum value.

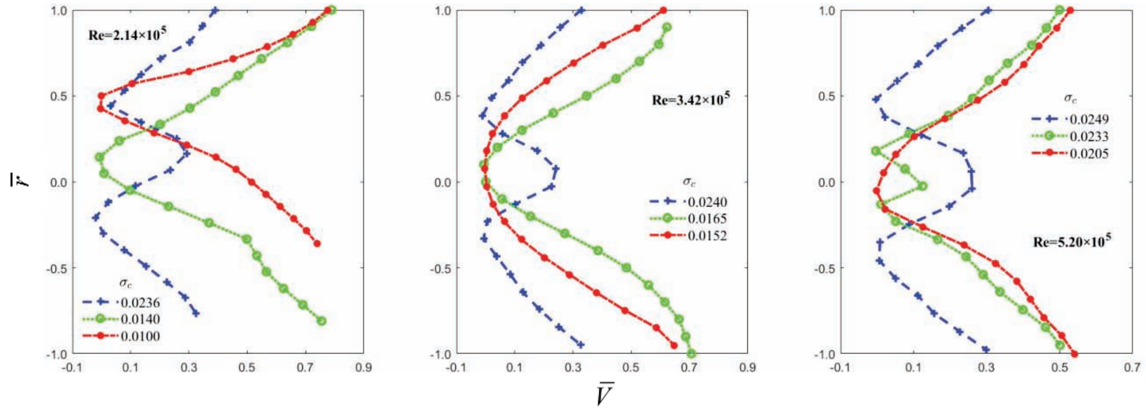

Figure 3(a) Gas velocity in the initial re-entrant section S_{t1}

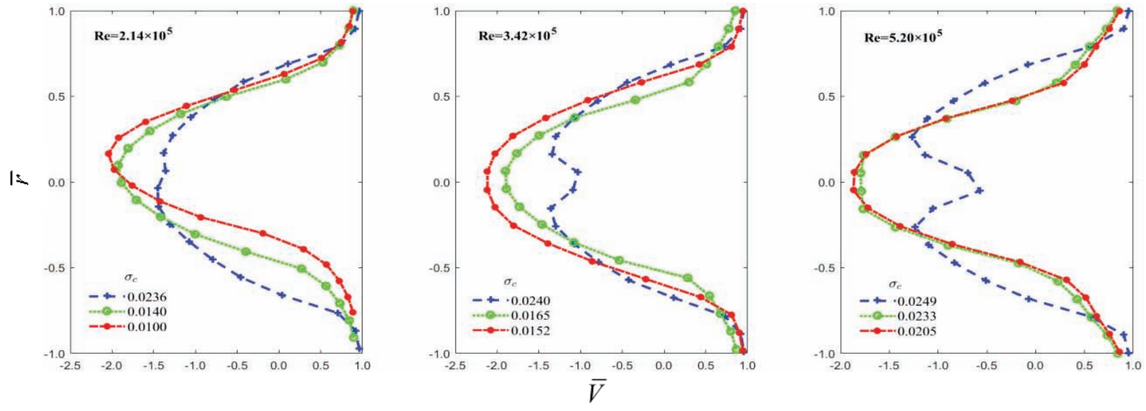

Figure 3(b) Gas velocity in the maximum velocity section S_{t3}
Figure 3 Gas velocity distributions in the characteristic sections

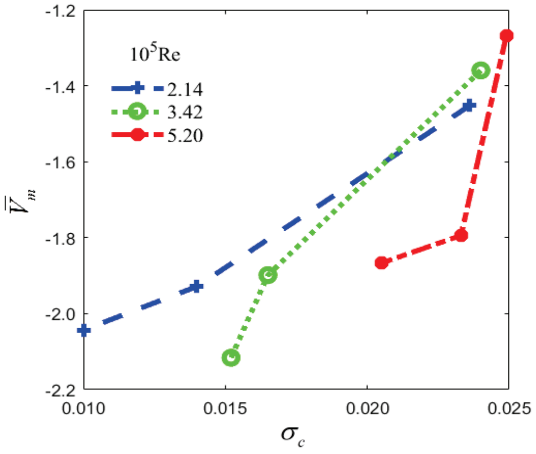

Figure 4 Maximum gas velocities inside supercavities

Conclusion

The developed multi-fluid model is applied to reveal flow structures in the re-entrant flow region for ventilated supercavitating flows at high speed. Re-entrant gas flows occur under the adverse pressure gradient, and the velocity distribution characteristics are presented at different Reynolds and cavitation numbers. Due to the multiple relationship between the maximum gas and inflow velocities, gas compressibility needs to be considered for high-speed ventilated supercavitating flows.

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