Multiphase flow characteristics and gas loss in the shear layer on a ventilated supercavity wall

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Introduction

Ventilated supercavity has been paid much attention to reduce the drag of underwater bodies. However, it is hard to maintain and control a stable motion of supercavity during a long time. The key point is how to accurately predict the supercavity shape on complicated flowing conditions. Only after the gas loss law of supercavity is understood deeply can we determine the ventilation amount, control the supercavity size and ultimately make the body perform better.

Computational model

Due to the concentrated distribution of gas and liquid phases in ventilated supercavitating flow, we consider the mass and momentum transports of non-condensable gas, vapor and water, and develop the multi-fluid model really suitable for simulating large-scale the supercavity and revealing the interactions between different phases.

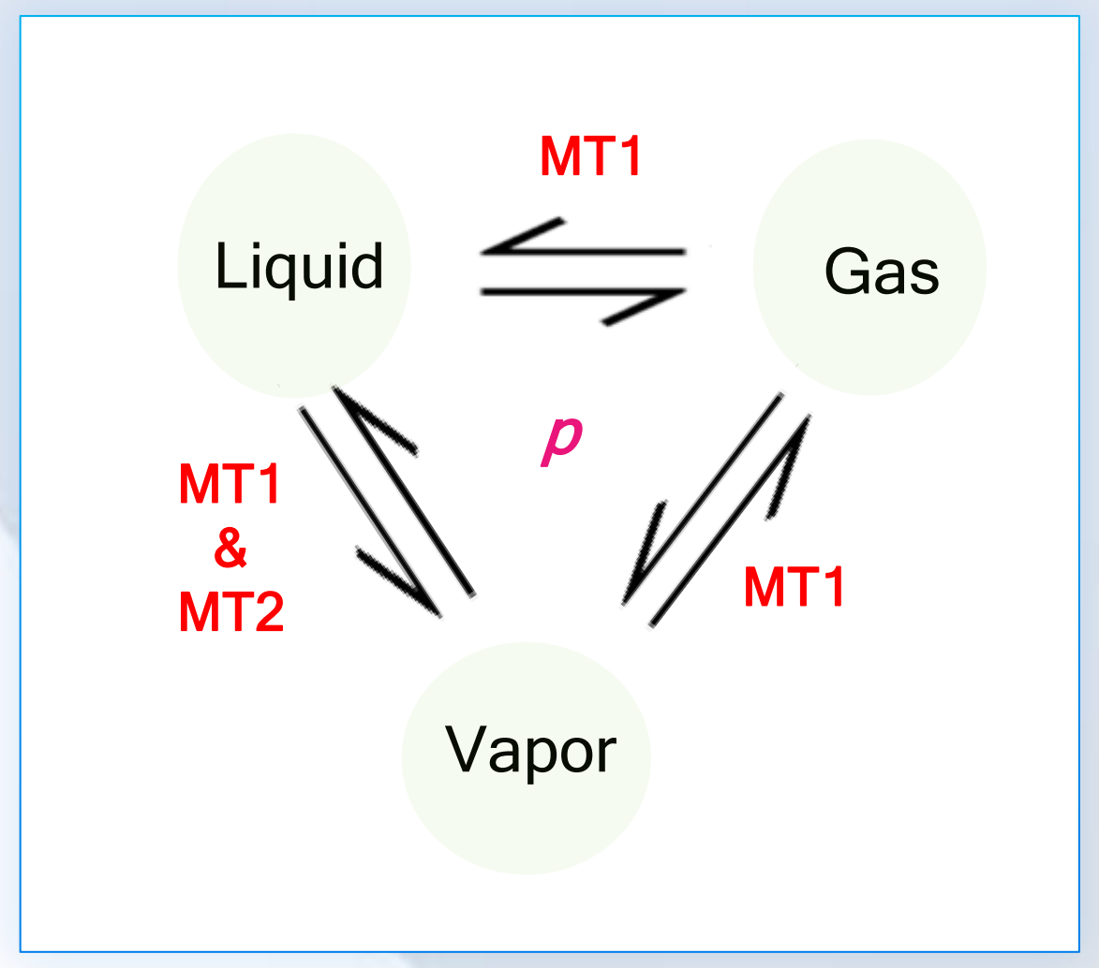


FIG. 1. Principle scheme of the Multi-fluid model

Governing equations for each phase

Momentum transport (MT1)

$$M_\alpha = \sum_{\alpha\neq\beta} C_d\rho_{\alpha\beta}A_{\alpha\beta}|\boldsymbol{U_\beta}-\boldsymbol{U_\alpha}|(\boldsymbol{U_\beta}-\boldsymbol{U_\alpha})$$

Mass transport (MT2)

$$\dot{m}^+ = F_v\frac{3\gamma_{nuc}(1-\gamma_v)\rho_v}{R_{nuc}}\sqrt{\frac{2|p_v-p|}{\rho_w}}$$

$$\dot{m}^- = F_c\frac{3\gamma_v\rho_v}{R_{nuc}}\sqrt{\frac{2|p_v-p|}{3\rho_w}}$$

Shear layer flow characteristics

Figure 2 displays the supercavitating flow patterns for the incoming velocities of 20 and 140 m/s, respectively, which correspond to typical supercavitation patterns under great and little gravity effect conditions of Fr= 15.0585 and Fr=105.3461.

The internal shear layer is much thicker than the external shear layer. The outer boundary of the external shear layer is not smooth, and there are no obvious longitudinal distribution characteristics.

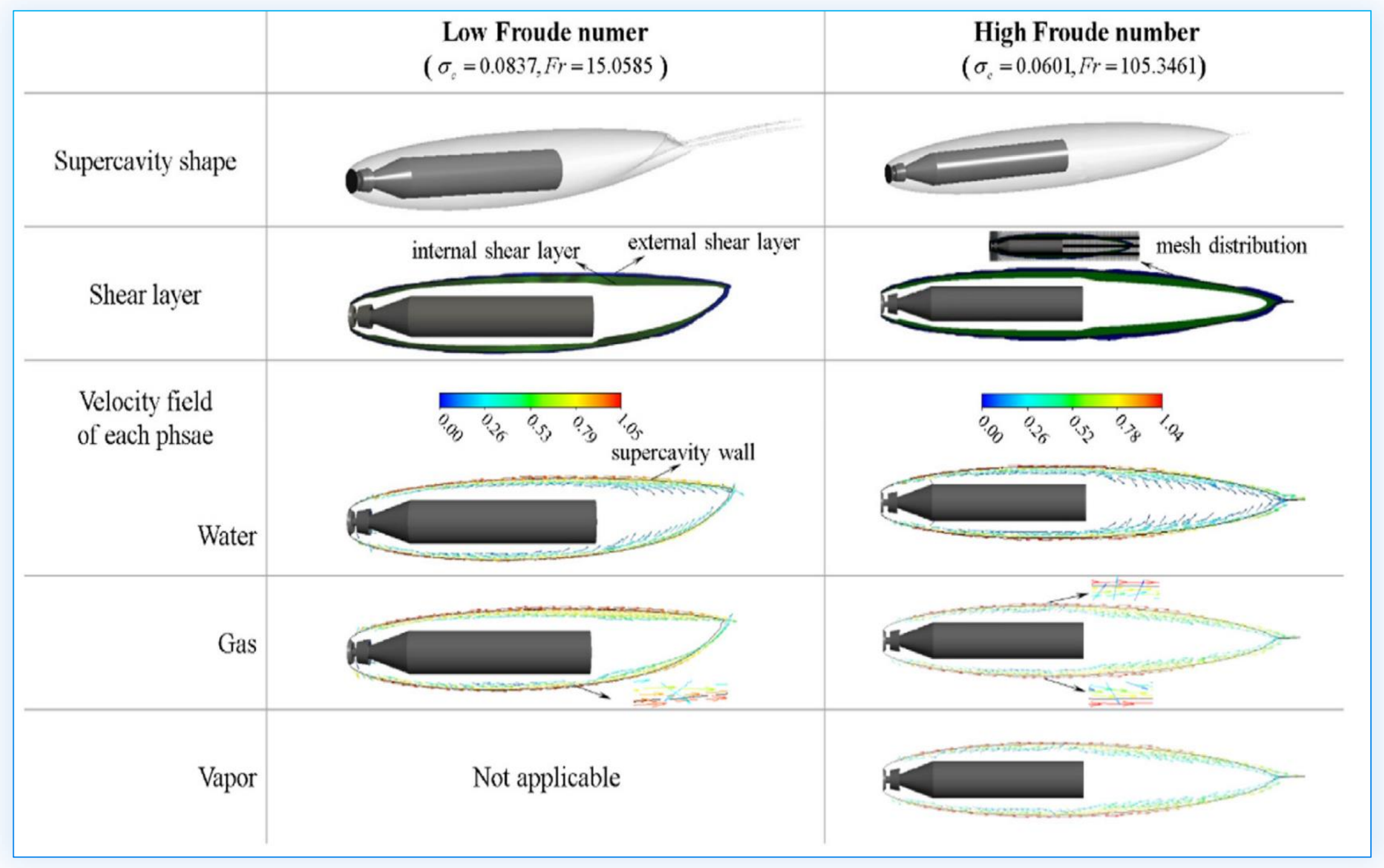
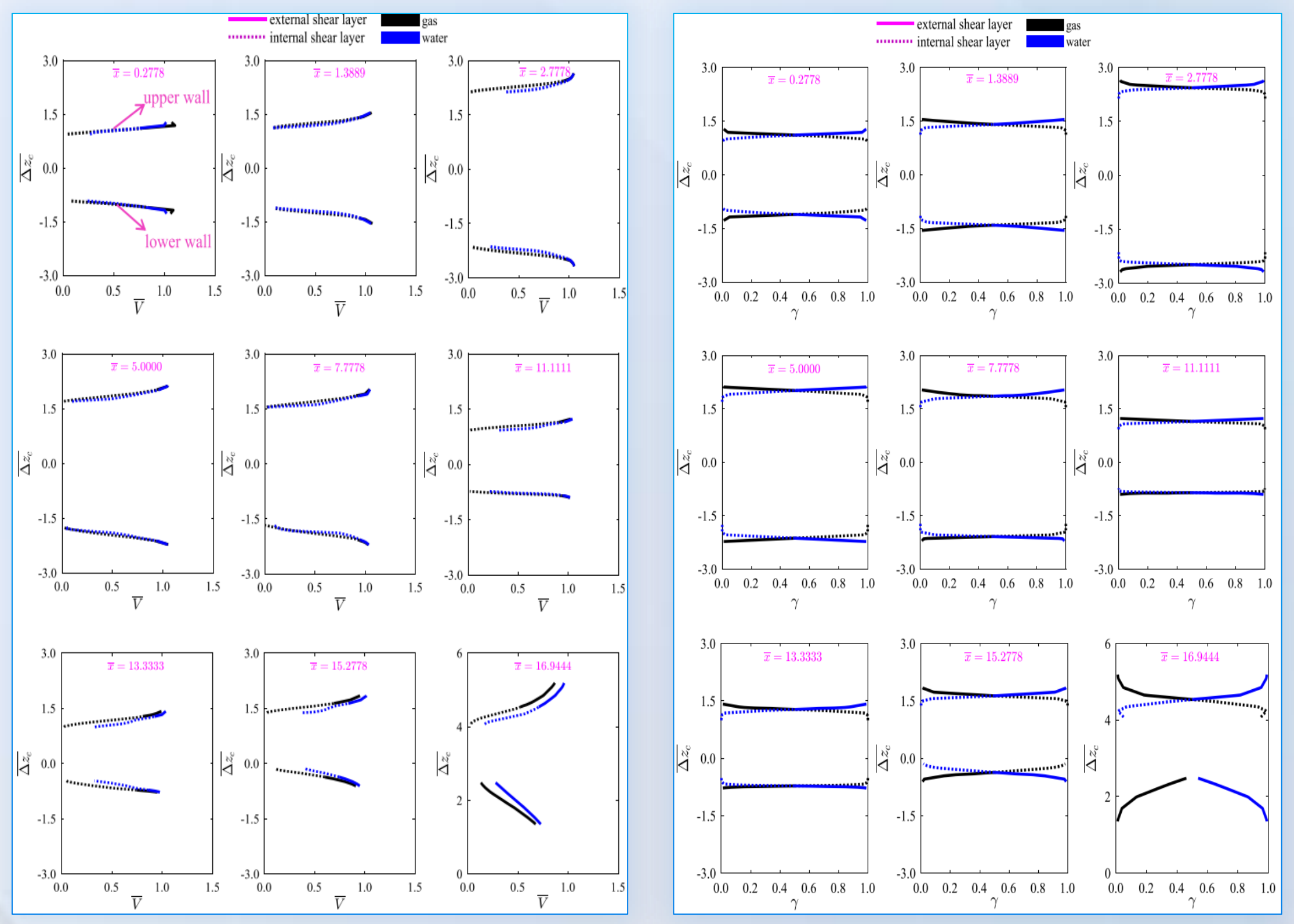


FIG. 2. Shear layers under typical ventilated supercavitating flow patterns

The flow parameters of each phase are analyzed in the shear layer by selecting several cross sections

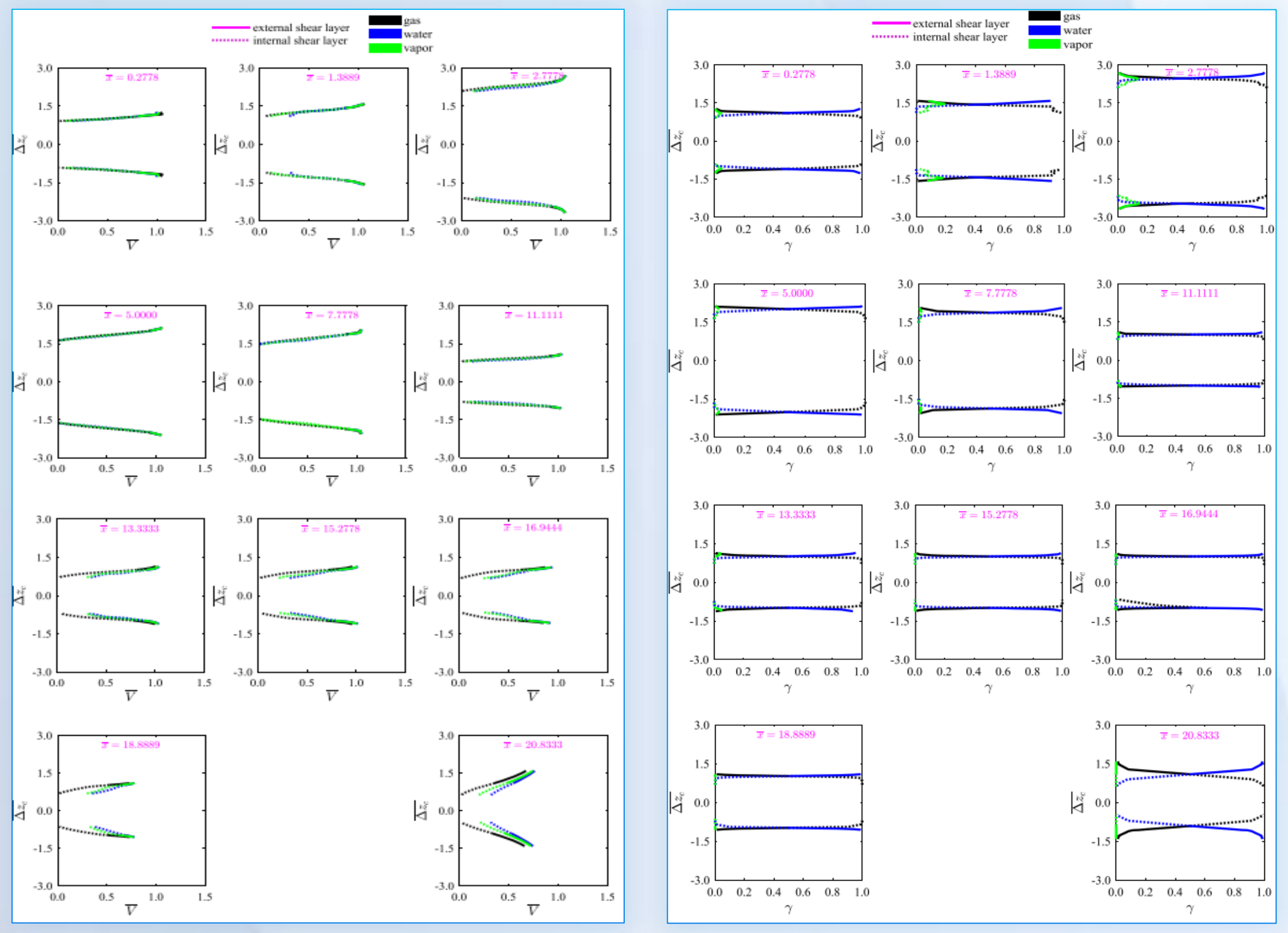


(a) Velocity (b) Volume fractions

FIG. 4 Radial distributions of gas and water flow parameters in the shear layer (σ_c=0.0837, Fr=15.0585)

It can be seen that the above figure that the velocity distribution of each phase is similar and the gas phase velocity is slightly less than that of water. The velocity of each phase in the internal shear layer is linearly distributed along the radial direction. There are two different linear changing regions of the radial distribution in the external shear layer.

As for the volume fraction distribution of each phase, there exists an opposite distribution rule of the water and gas phase volume fractions. Besides, there is an abrupt change on both sides of the shear layer and approximately linear distribution in other regions.



(a) Velocity (b) Volume fractions

FIG. 5 Radial distributions of gas, water and vapor flow parameters in the shear layer (σ_c=0.0601, Fr=105.3461)

For the flows with little gravity effect, the velocity distribution of each phase is similar and the linear trend is more obvious. Natural cavitation occurs, and the vapor velocity is higher than that of gas but lower than that of water and the velocity differences between phases are enlarged along the longitudinal direction. The change rules of gas and water volume fractions are similar to those of low speed flow. The vapor exists in the region from x = 0 to x = 5, indicating that the natural cavitation mainly occurs in the supercavity head.

Conclusion

The multiphase flow and phase distribution characteristics in the shear layer on a ventilated supercavity wall are revealed. Based on the characteristics and using the theoretical analysis method, the shear-layer gas loss model of ventilated supercavities is established and validated.

This study presents a strong theoretical foundation and technical support for improving the supercavity dynamics model to control the supercavity shape and realize the complicated motion of supercavitating bodies.

Acknowledgements

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Shear-layer gas loss model

Based on the flow characteristics of each phase in the shear layer, the gas loss rate on the supercavity wall can be studied. According to the law of mass conservation, the shear flow rate is approximately equal to the gas loss of supercavity.

We focus on the shear layer to model the shear flow rate. According to the principle of momentum conservation, there is an integral expression in the shear layer, and the gas velocity and mixing density in the shear layer can be obtained based on the distribution law and boundary conditions. Therefore, the expression for calculating the shear layer thickness is obtained, and the gas loss model is established.

$$\int_0^{l_s} 2\pi R_c\tau_c dx = 2\pi R_c\int_0^{\theta_c}\rho_m V_m^2 dz_s$$

$$\int_0^{l_s} 2\pi R_c\tau_c dx = 2\pi R_c\int_0^{\theta_c}\left(\left(1-\frac{z_s}{\delta_c}\right)\frac{-\rho_g+\rho_w}{2}+\rho_g\right)V_g^2 dz_s$$

$$\theta_c = \frac{\int_0^{\delta_c}(V_g'-V_g)V_g dz_s}{V_c^2}$$

$$\delta_c = \frac{324D_n(\rho_g+\rho_w)\sqrt{1+\sigma_c}\int_0^{l_s}\sqrt{\left(\frac{R_n}{x}\right)^2+\sqrt{\frac{2(C_d-k_c\sigma_c)}{k_c\mu_c}}\frac{R_n}{x}-\frac{\sigma_c}{2\mu_c}}dx}{(87\rho_g+65\rho_w)Re_d\bar{\delta}_x R_c}$$

Gas loss model

$$\bar{Q}_{out} = \frac{216\pi(\rho_g+\rho_w)(1+\sigma_c)\int_0^{l_c}\sqrt{(\frac{R_n}{x})^2+\sqrt{\frac{2(C_d-k\sigma_c)}{k_c\mu_c}}\frac{R_n}{x}-\frac{\sigma_c}{2\mu_c}}dx}{(87\rho_g+65\rho_w)Re_d\bar{\delta}_x D_n}$$

To validate the model, the theoretical solutions are compared with the numerical simulations of ventilated supercavitating flows in an unbounded field and the experimental results in the figure below. Overall, the shear-layer gas loss model is validated.

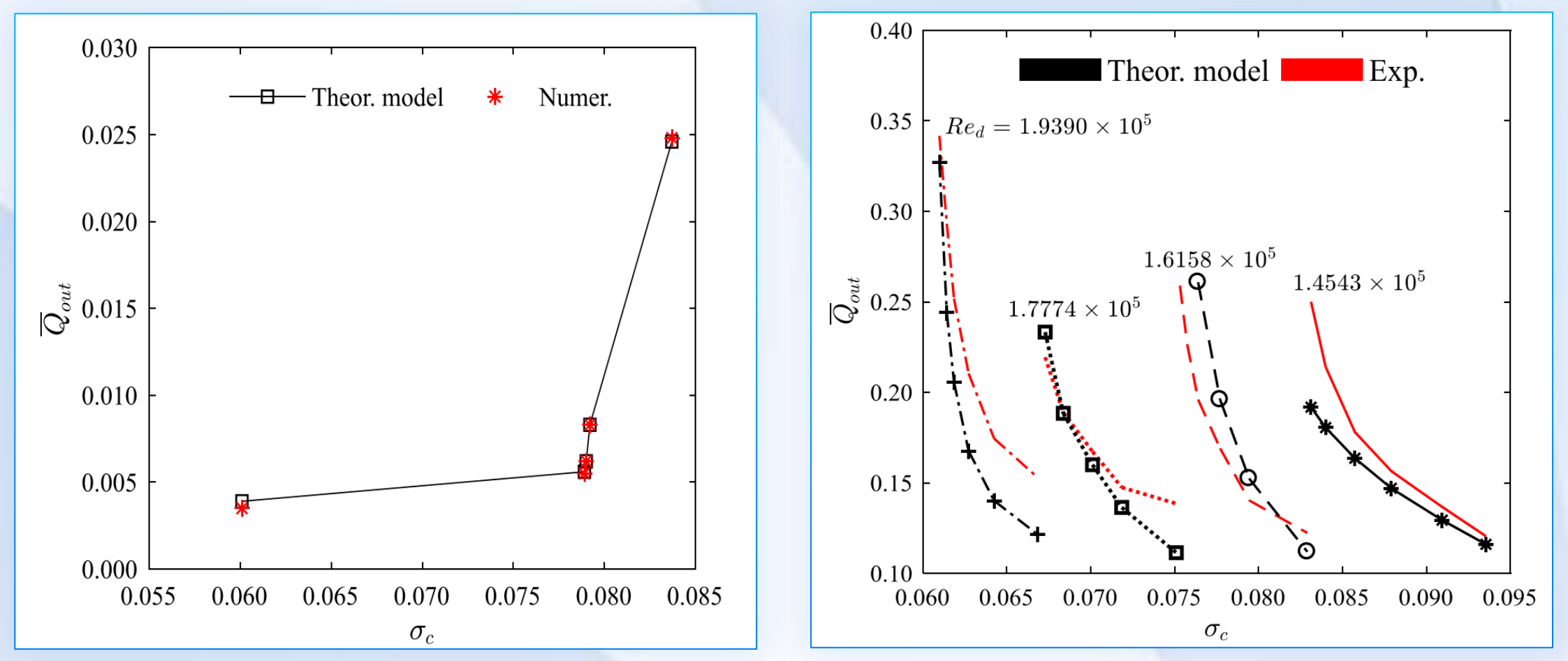
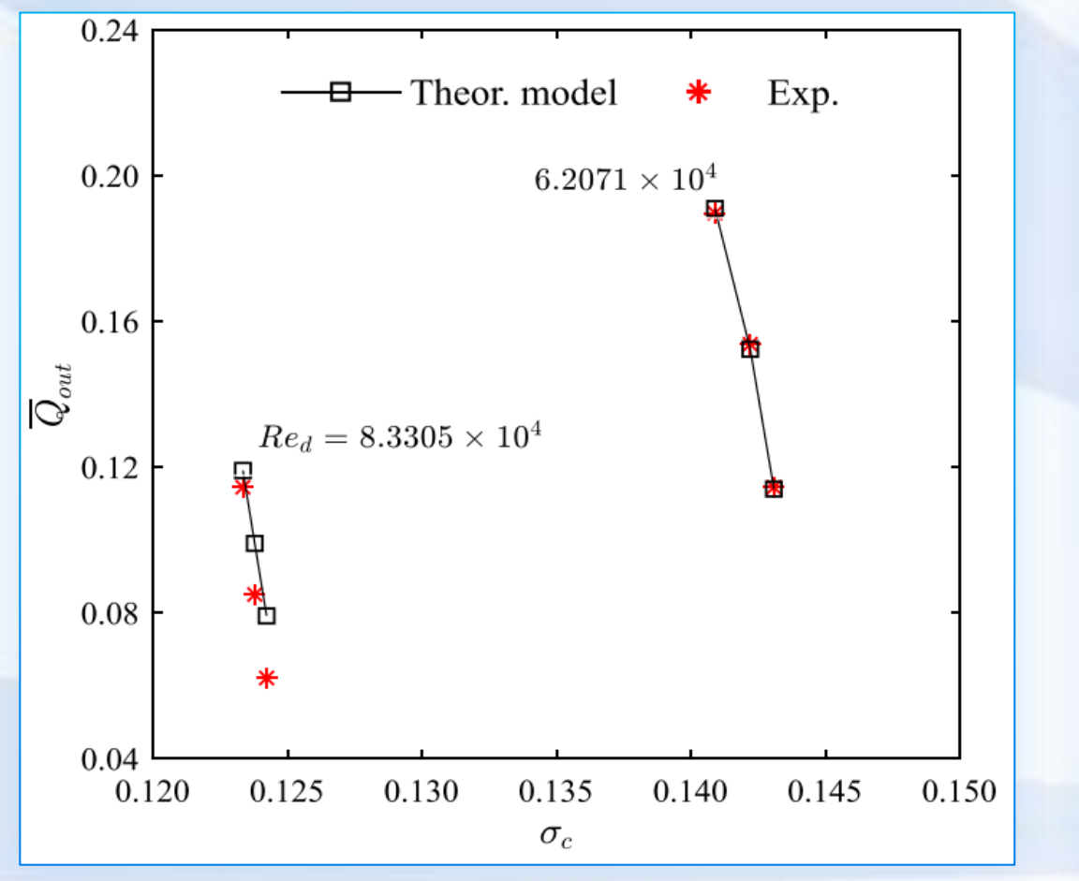


FIG. 6. Gas loss law of ventilated supercavitating flows



(a) high-speed flows in an unbounded field,
(b) low-speed flows in a water-whirling arm experiment, and
(c) low-speed flows in a water tunnel experiment.