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Critical penetration condition and Ekman suction-extraction mechanism of a sink vortex

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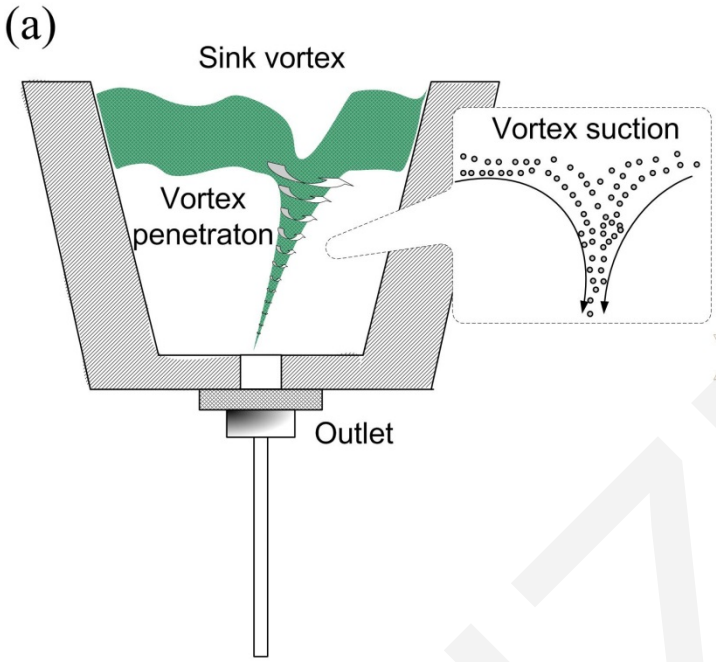
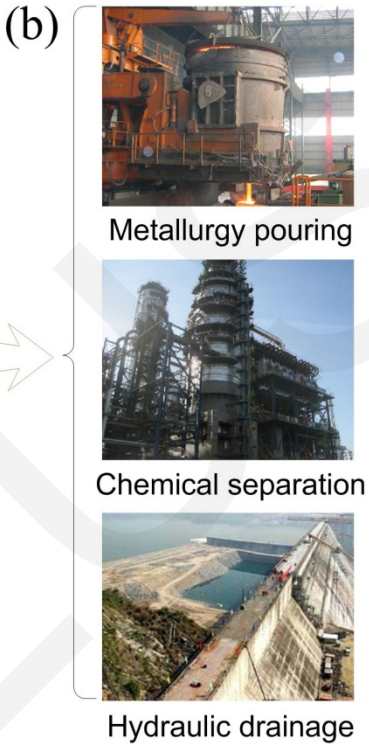
Free sink vortex and instances

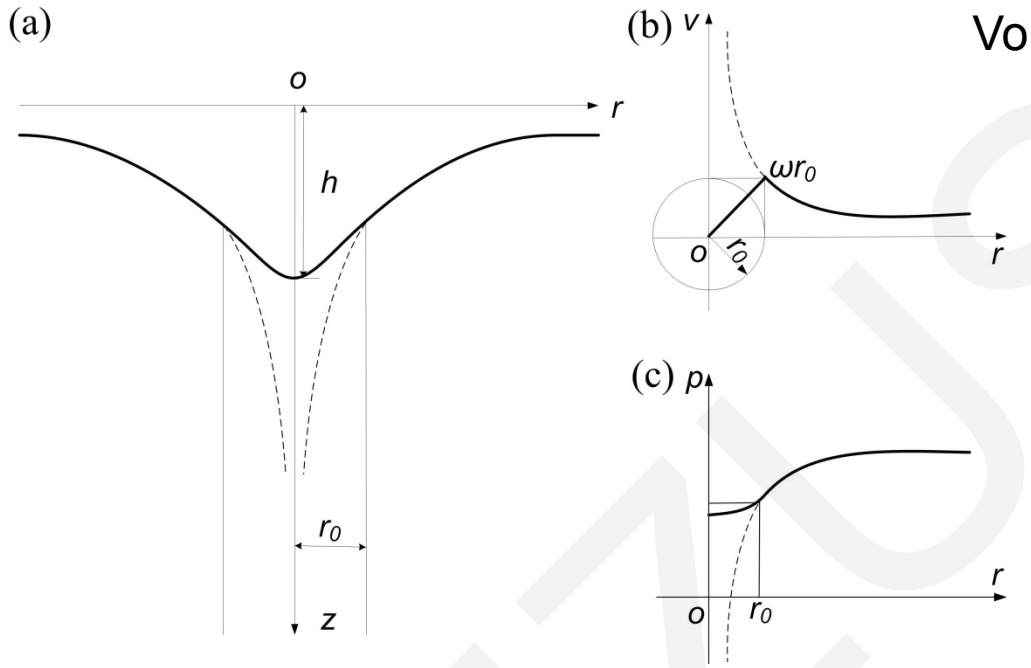




(**a**) When the rotation energy breaks through the liquid surface tension, the vortex is **penetrating**, and the surface layer liquid will be sucked into the vortex core.

(**b**) Sink vortex occurs in some industrial areas, such as **metallurgy pouring**, **chemical separation** and **hydraulic drainage**.

Helmholtz-equation-based solution method



Theoretical model of Rankine vortex

Vortex described by Helmholtz equation

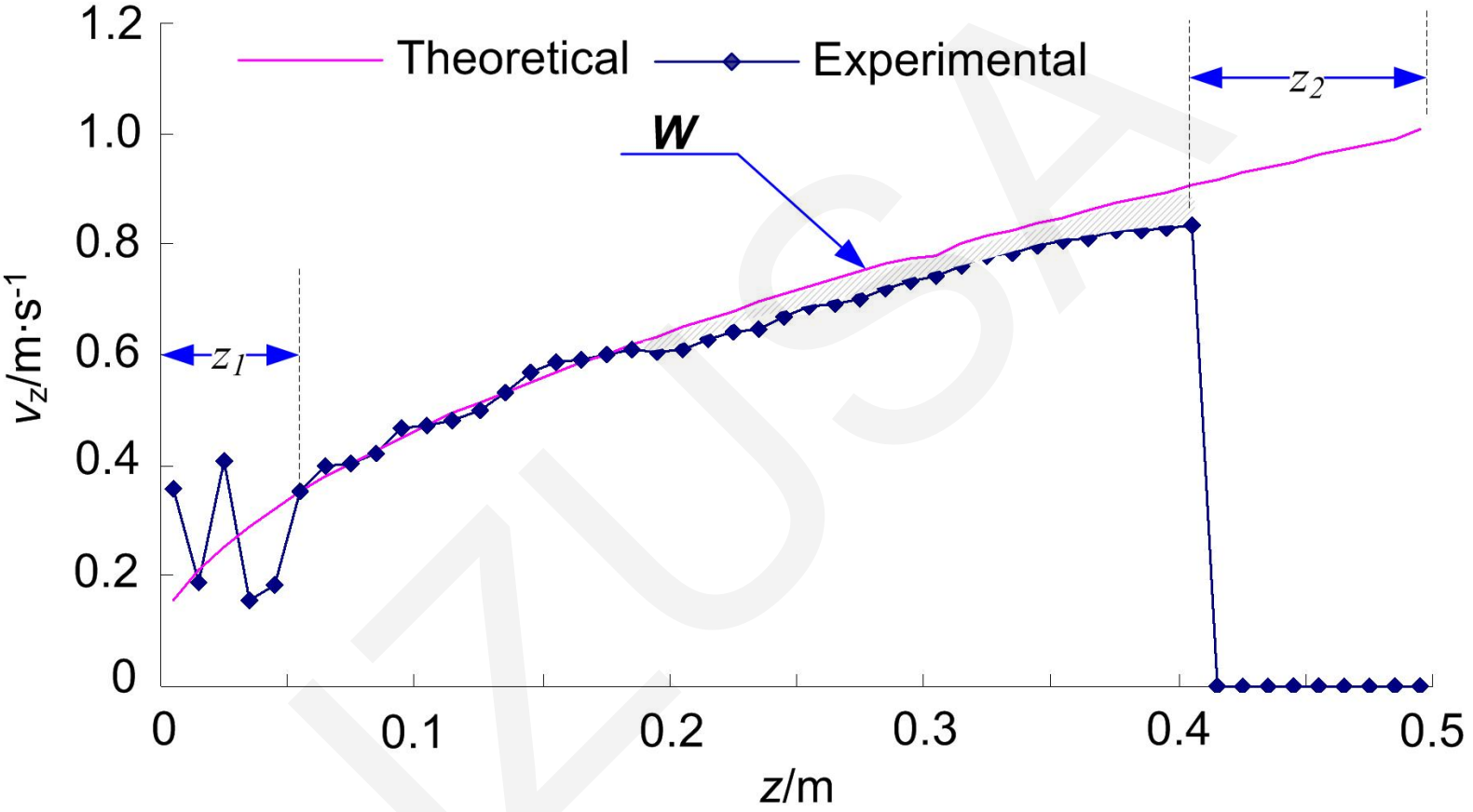
$$\frac{\partial \Omega}{\partial t} + (v \cdot \nabla)\Omega = (\Omega \cdot \nabla)v + \nu \nabla^2 \Omega$$

$$\Rightarrow \frac{\partial \omega_i}{\partial t} + v_j \frac{\partial \omega_i}{\partial x_j} = \omega_i \frac{\partial v_j}{\partial x_j} + \nu \frac{\partial^2 \omega_i}{\partial x_i x_j}$$

Critical penetration condition

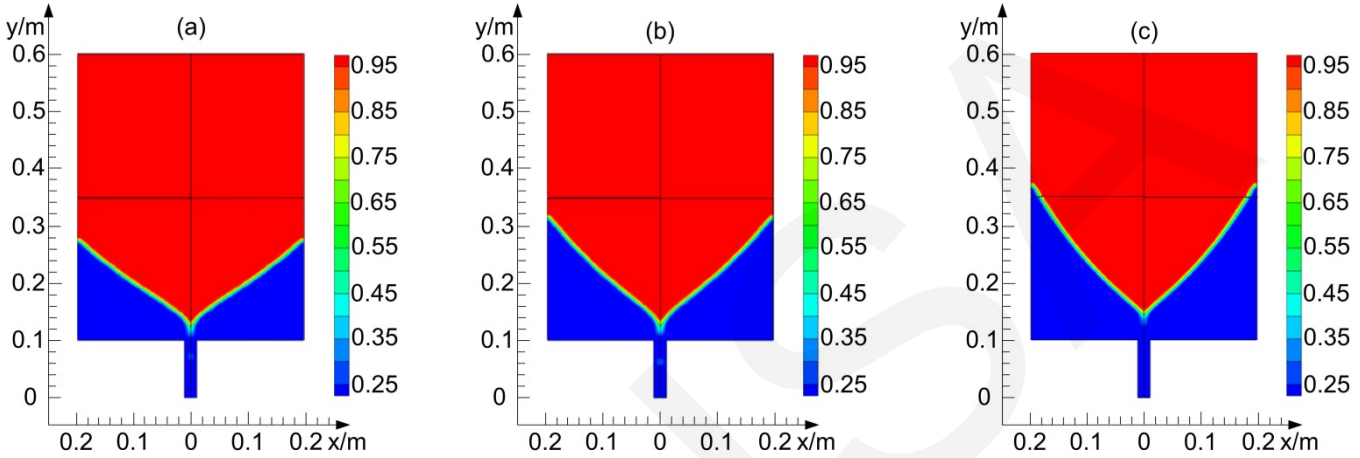
$$\frac{\partial v_z}{\partial z}\left(v_z + \frac{\Gamma^2}{2\pi^2 r_0^2}\frac{1}{v_z}\right) = g$$

Critical penetration condition

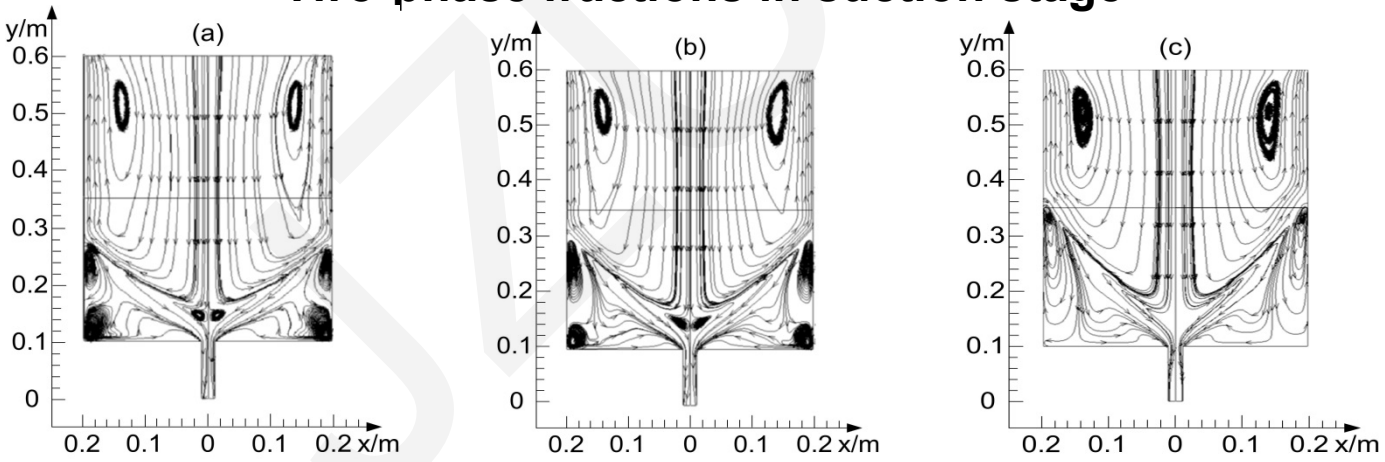


In the upper zone of the curve, the rotation energy would break through the surface tension, and the vortex would enter the penetration state.

Suction-extraction of Ekman layer

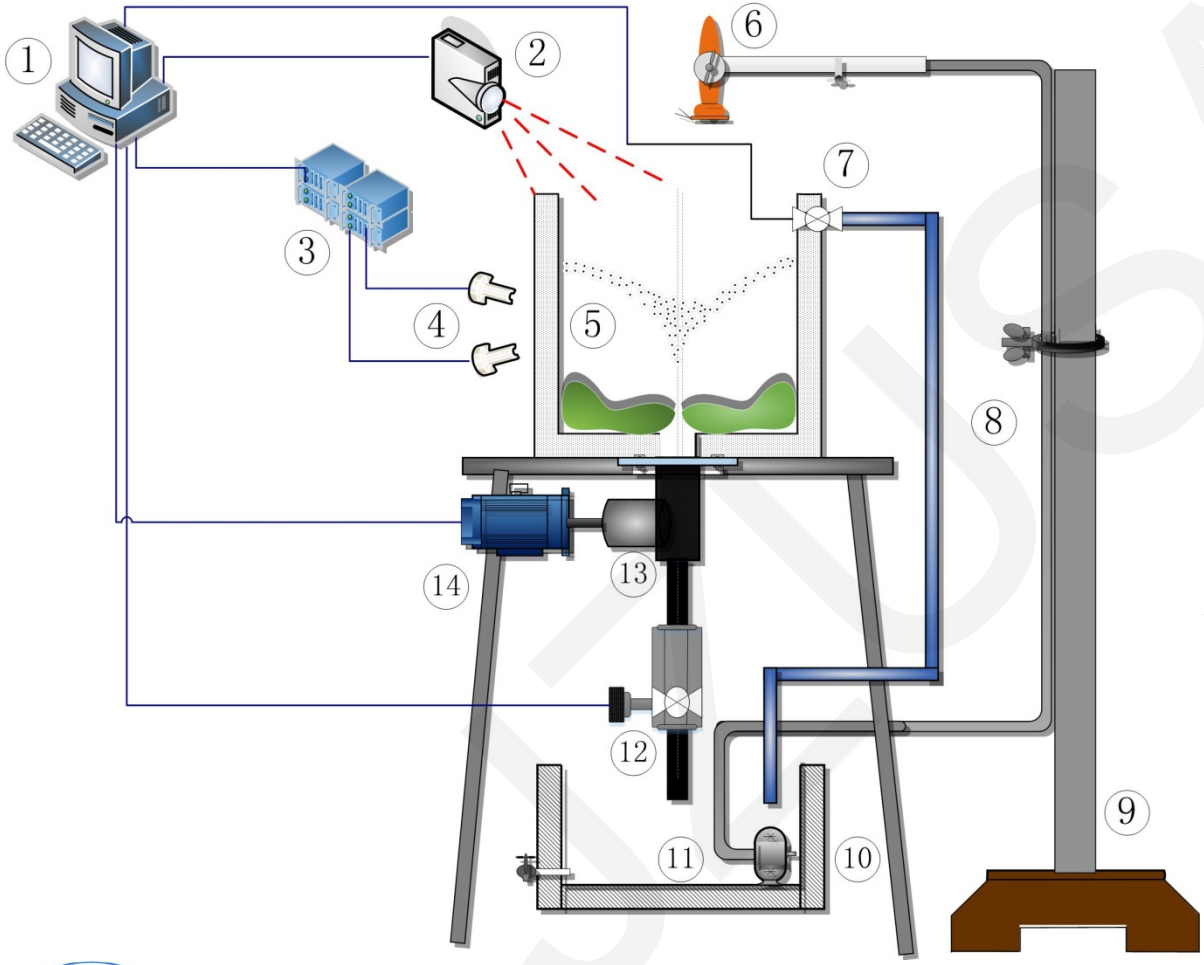


Two-phase fractions in suction stage



Stream lines of extraction stage

PIV observation experimental platform

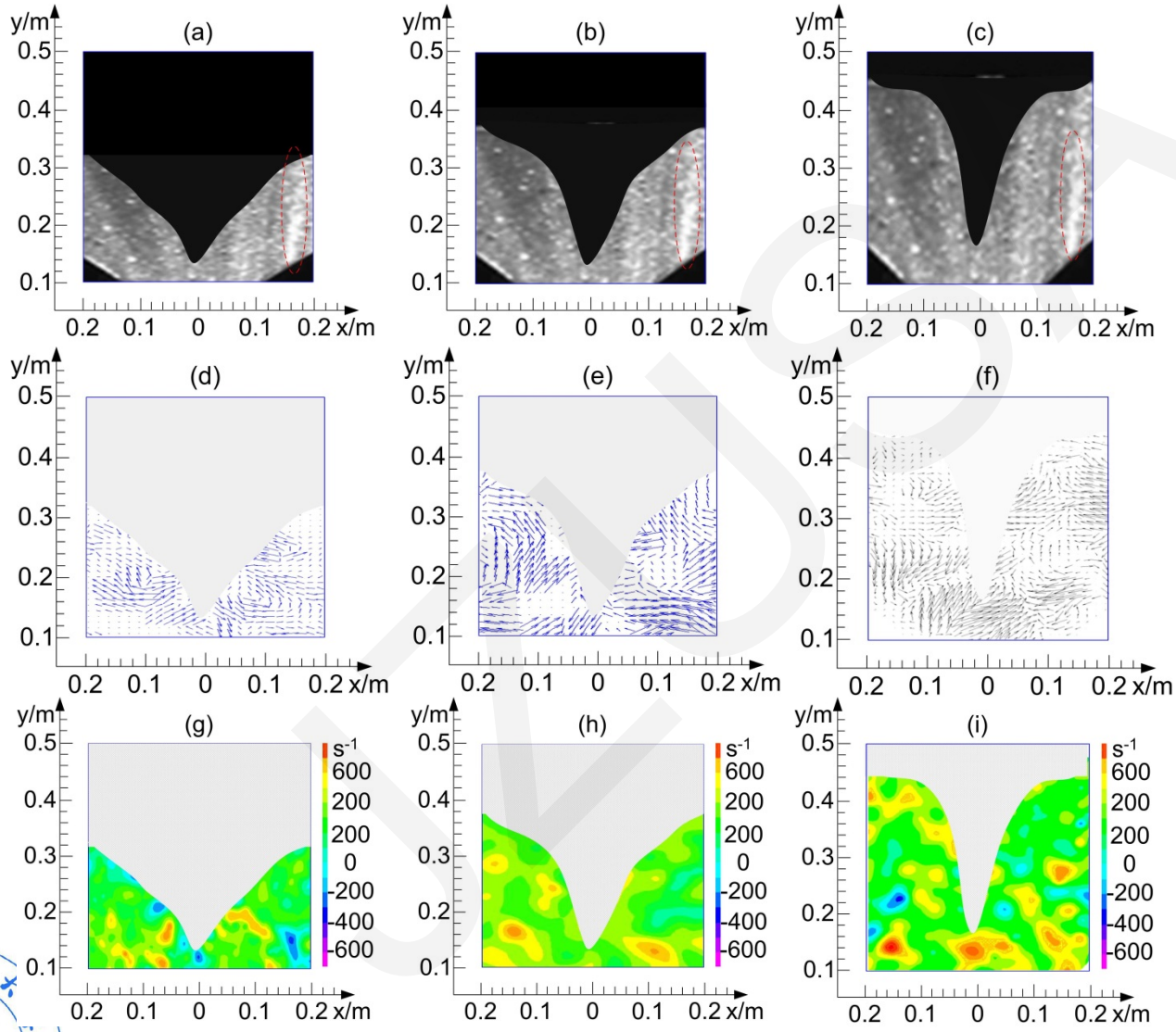


A binocular endoscopy is adopted to capture the real-time vortex image.

A sink vortex generation device is constructed to provide the required vortex in the measurement range of endoscopy.

A high frequency laser to generate the ultra-fast pulses, and a post-processing system to obtain the velocity vector and vorticity contour.

Observation results



(a)-(c) The vortex photos on three initial rotating velocities. The highlight zone is the **boundary of vortex**.

(g)-(i) The fluid vorticity is **aggregating to the vortex end**, which is a transition process of turbulent kinetic energy.

Conclusions

- The critical penetration condition of sink vortex contains multiple solutions that are caused by different initial flow field states.
- The heights of suction/extraction holes to container bottom are decided by the geometrical parameters, and have no relation to the initial velocity components.
- If the initial disturbances are enhanced, the suction-extraction height and Ekman layer thickness become larger, but the Ekman boundary vorticity intensities of two stages (suction, extraction) take on descending trend.