§3. Surface Wave Structure and Control of Vertical Liquid Film Flow

Kunugi, T.C., Kino, C., Serizawa, A. (Kyoto Univ.),
Sagara, A.

It is very important to grasp and understand the falling film flow behavior along the vertical wall from the heat and mass transport point of view in many engineering fields [1]. According to the stability theory, the vertical falling film flows are always unstable and various types of surface waves are appeared due to the non-linear wave interactions such as a solitary wave and a capillary wave, etc. Although the heat and mass transfer are certainly enhanced by these waves, the enhancement mechanism is not well understood until today. There are many experimental studies for investigating the film flow characteristics. However, most of numerical studies are focused on the two-dimensional laminar liquid film flow because of the limitation of computer power and the difficulty of the free surface treatment numerically [2].

The governing equations are the continuity for multi-phase flows, momentum equation based on the one-filed model and the energy equation as follows:

$$\frac{\partial F_m}{\partial t}+\nabla\left(F_m V\right)-F_m \nabla V=0 \tag{1}$$

$$\frac{\partial V}{\partial t}+\nabla\cdot(VV)=G-\frac{1}{<\rho>}(\nabla P-F_V)-\nabla\cdot\tau. \tag{2}$$

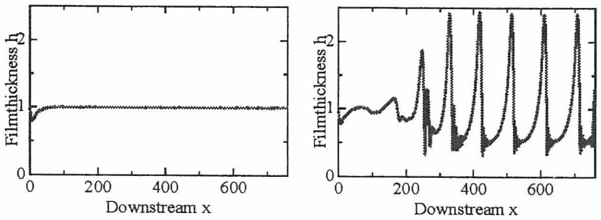
Here, F is the volume fraction of fluid, λ is the thermal conductivity and the suffix m denotes the *m*-th fluid or phase, < > denotes the material average and F_V is body force due to the surface tension based on the CSF (Continuum Surface Force) model. The interface tracking technique is based on the MARS (Multi-interface Advection and Reconstruction Solver) [3].

As for the 2D simulation, the mesh sizes are (Δx, Δy)=($0.4h_0$, $0.1h_0$) and (Δx, Δy, Δz)=($0.6h_0$, $0.2h_0$, $1.0h_0$) for 3D simulation. Here, h_0 is an equilibrium liquid film thickness. The inlet mean velocity U_0 can be controlled by the external forcing as expressed:

$$U=\left[1+\varepsilon\sin(2\pi ft)\right]U_0 \tag{3}$$

Here, the forcing frequency is *f*. *f*=0Hz, 13Hz, 20Hz and 45Hz are considered in the present study. Reynolds number (Re=U_0h_0/ν) is set to 75 that is a critical Re [4]. ε is set to 0.03 as same as the reference [2]. The outflow boundary is assumed to be a zero pressure gradient, the airside boundary surrounding the solution domain is assumed to be a constant pressure. At the wall, the non-slip velocity condition is applied.

Figures 1-(a), (b) show the film thickness distribution for 0 and 20 Hz, respectively. According to the stability theory, the vertical falling film flows are always unstable [4]. The film thickness shown in Fig. 1(a) is very stable. It might be depending on the computational mesh size. As for (b), the liquid film becomes unstable in the downstream region, and eventually the solitary wave and the capillary waves in front of the solitary one are developed. The numerical results of the relationship between the peak height of solitary wave and the frequency is very good agreement with the experiments as shown in Fig.2. Figure 3 (a) shows the streamlines on the moving coordinate with the wave celerity. A large recirculation flow can be seen in the solitary wave. Figure 3 (b) shows the velocity vector and the vortices can be seen between waves. There is no report on these vortices in the previous experimental and numerical studies. This finding is very important to control the free-surface film flow on the vertical wall of the fusion reactors.



(a) Re=75, 0Hz (b) Re=75, 20Hz

Fig 1 Fully developed film thickness behavior

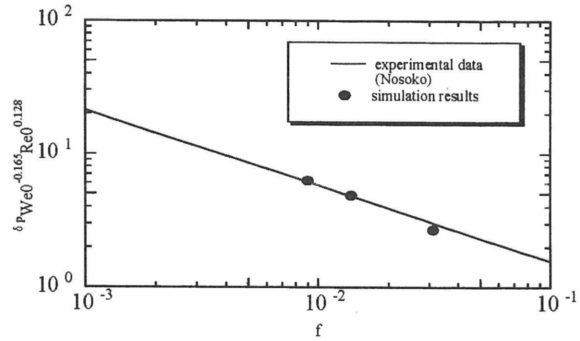


Fig.2 Comparison of wave peak height between simulation and experimental data [1].

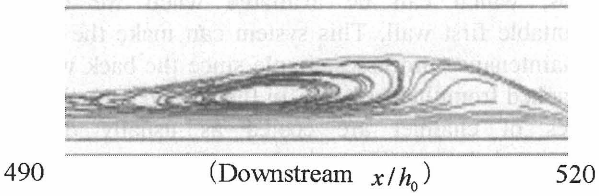


Fig.3 (a) Streamlines observed from moving coordinates with wave celerity for Re = 75, 20Hz.

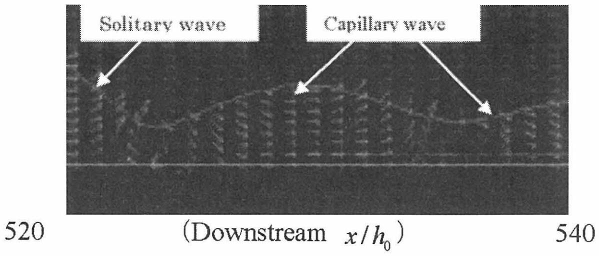


Fig.3 (b) Vector of velocity for Re = 75,20Hz.

References

1) Nosoko, T., Chem. Eng. Soc., 51(1996)725
2) Miyara, A., Int. J. Therm. Sci . 39(2000)1015
3) Kunugi, T., Comput. Fluid Dynamics J., 9(2001)563
4) Alekseenko, S. V., *Wave Flow of Liquid Films*, Begell House, New York (1994)