Surface Flow Simulation of Falling Films on a Vertical Plane

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1. Introduction

The reactor containment in a nuclear power plant provides the principal barrier to prevent the release of radioactive materials into the environment. During a severe accident, analysis of water/steam behaviors plays a vital role in avoiding both a hydrogen explosion and steam overpressure in the containment. Accidents including the water spray and steam injections form a continuous liquid film on the surface of structures and components. Consequently, the liquid film dynamics affects the steam condensation on the cooling surface and becomes an important factor in ensuring the structural integrity of the containment.

The lumped model approach such as the MELCOR simulation has shown reasonable agreement with experimental data[1]. However, its simplified models limit the application scope and reveal a large uncertainty for the accident prediction with a complex geometry. The liquid film models in the MELCOR also have been developed for the scaling analysis and its behavior is predicted based on the simplified correlations. To overcome these limitations, a multi-dimensional approach has been employed with significant improvements of computational power.

Several researches have been conducted on surface flow dynamics of falling films. Initial works were achieved through experimental measurement and developed analytical models. Nusselt first proposed a correlation to characterize the film thickness and velocity of falling films[2]. Kapitza and Braune developed thickness correlations for downward falling films on a flat plate[3,4]. Volume-of-Fluid (VoF) method is also used to track the liquid-gas interface. However, the VOF method requires high computational cost. To reduce the computational cost and elucidate the surface curvature, thin film models are employed to simulate thin liquid transport over solid surfaces. Tuković and Jasak presented 2D simulations of a thin liquid film on an arbitrary surface using the Finite Area (FA) method[5]. Meredith et al. developed the surface thin model based on the Finite Volume (FV) method in OpenFOAM[6]. In particular, it also implemented various physical models to account for realistic liquid film flow over 2D surface such as partial-wetting, thermo-capillary, droplet injection and separation, etc.

This study has estimated the FVM-based liquid film solver implemented in OpenFOAM. Numerical simulations are conducted for surface falling films on a vertical plate.

2. Numerical Methods

Since liquid film over solid surfaces is very thin, the surface-normal flow can be assumed to be negligible. In addition, the surface-tangential diffusion of mass, momentum and energy are also insignificant compared to the surface-normal diffusion. The velocity profile along the film is assumed to be quadratic. These assumptions simplify the 3D transport to the 2D surface flow by integrating the velocity distribution through the film. Thus, the continuity equation can be written as follows:

$$\frac{\partial \rho\delta}{\partial t} + \nabla_s \cdot [\rho\delta U] = S_{\rho\delta} \tag{1}$$

where ρ and δ are the liquid density and film thickness, respectively. U is the integrated average velocity along the film. $S_{\rho\delta}$ is the mass source per unit area representing the mass change due to droplet impingement, splashing, evaporation, film separation, etc.

The momentum equation is defined as

$$\frac{\partial \rho\delta U}{\partial t} + \nabla_s \cdot [\rho\delta UU] = -\delta\nabla_s p + S_{\rho\delta U} \tag{2}$$

where $S_{\rho\delta U}$ represents the momentum source through the film. The pressure p consisted of spray impingement (p_{imp}), splashing (p_{splash}), vapor recoil effect (p_{vap}), surface tension (p_σ), hydrostatic head (p_δ), gas pressure (p_g).

$$p = p_{imp} + p_{splash} + p_{vap} + p_\sigma + p_\delta + p_g \tag{3}$$

The momentum source $S_{\rho\delta U}$ is the summation of stress-based terms and external momentum gain or loss.

$$\begin{aligned} S_{\rho\delta U} = \tau_g - \tau_w + \tau_{mar} + \rho g_l \delta + F_\theta \\ + S_{\rho\delta U,imp} + S_{\rho\delta U,splash} + S_{\rho\delta U,sep} \end{aligned} \tag{4}$$

The first two terms represent the shear stress at the gas and wall interfaces, respectively. τ_{mar} is the thermocapillary force. $\rho g_l \delta$ and F_θ are the surface-tangential gravity force and the contact-angle effect, respectively. The last three terms are the momentum gain or loss due to impingement, splash and separation.

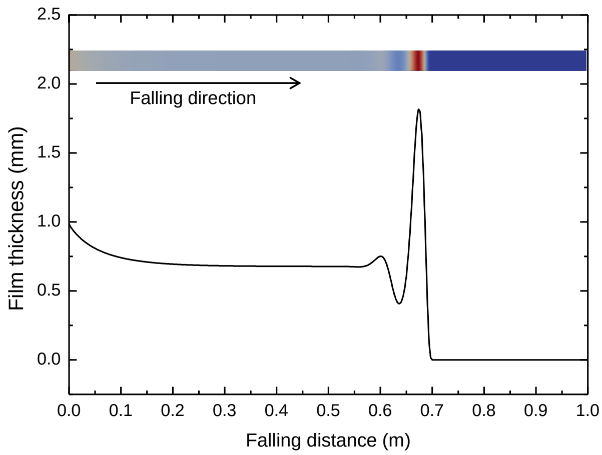


Fig. 1. Spatial distribution of the liquid film thickness at 0.5 seconds

3. Results

To validate the liquid film solver, a simple 1D falling film is first employed along a vertical plane of 1 m height. The liquid film falls down with a thickness of 1 mm and a velocity of 1.015 m/s. The number of nodes along the vertical flow path is 300. It takes 0.67 second to completely fall down from the top to the bottom. Due to the wall friction, the liquid film moves slower than expected from the initial velocity. Figure 1 displays a spatial distribution of the liquid film thickness at 0.5 seconds. As the liquid film progresses from the inlet, the thickness deceases and converges to a constant value. The front section of the falling liquid film provides a wrinkled curvature. To overcome a contact force between the wet and dry regions, a sufficient film thickness is required at the front section.

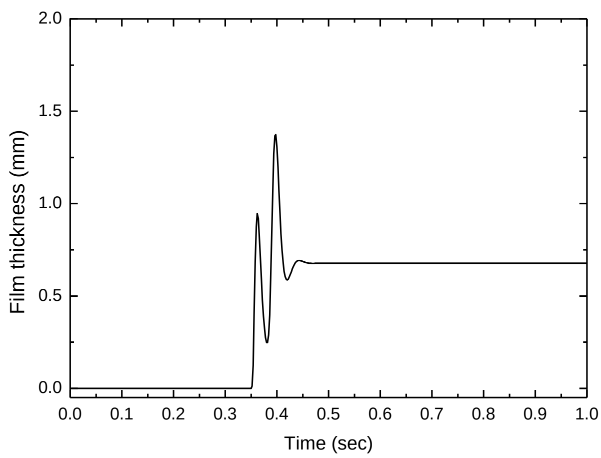


Fig. 2. Transient variation of the liquid film thickness at a height of 0.5m

Figure 2 shows the transient variation of the liquid film thickness at a height of 0.5m. The liquid film starting from the top of the vertical wall arrives in approximately 0.35 seconds. The front section also oscillates as expected from the spatial distribution in Fig. 1. The thickness of the liquid film converged to a constant value approximately 0.1 seconds after the first arrival.

The Nusselt theory provides an analytical solution for a falling film[2]. For a surface flow over an inclined flat surface, the steady-state mean film thickness and velocity can be calculated as follows:

$$\delta = \left(\frac{3\nu^2}{g\sin\theta_{inc}}\right)^{1/3} Re_f^{1/3} \quad (5)$$

$$U = \left(\frac{\nu g\sin\theta_{inc}}{3}\right)^{1/3} Re_f^{2/3} \quad (6)$$

$$Re_f^{1/3} = \frac{\delta U}{\nu} \quad (7)$$

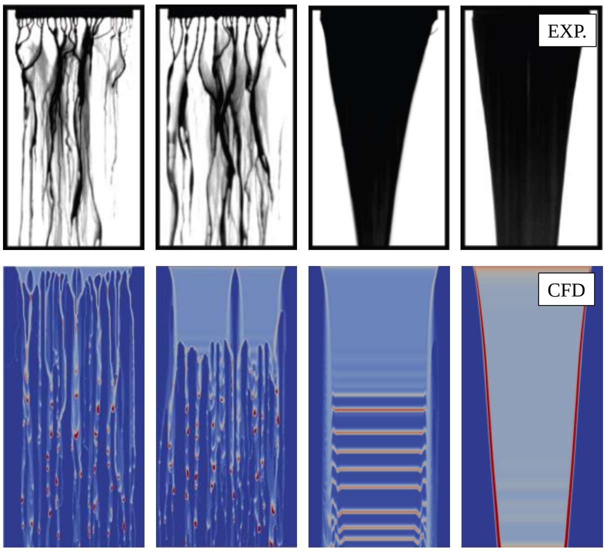
where ν and θ_{inc} are the kinematic viscosity and the inclination angle of surface, respectively. The film Reynolds number can be written in terms of the average film thickness and velocity. The comparison between Nusselt model and numerical results is summarized in Table I. The differences for the steady-state film velocity and thickness are about 0.022% and 0.061%, respectively.

Table I: Comparison of the steady-state film velocity and thickness

	Velocity (m/s)	Thickness (mm)
Nusselt theory	1.49909	0.677079
OpenFOAM	1.49942	0.677494

The 2D liquid film behavior of partially wetted flow over a vertical plane is examined to validate the liquid film solver. This study can elucidate the liquid film phenomena such as wet/dry separation, rivulet formation, isolated wet droplets, etc. Meredith et al. conducted experimental measurement for film flow over a vertical surface for a wide range of flow rates[7]. The test section was made of the cast acrylic plate of 0.61m wide and 1.22m long. The uniform water flow of 43℃ was discharged with a width of 0.51m onto the test plate. The falling liquid films were visualized by IR camera. The simulation using the liquid film solver is performed to predict the 2D partially wetted flow. The computation node over the test plate consists of 300 x 480.

Figure 3 exhibits the 2D spatial distribution of the liquid film for a wide range of flow rates. In the experiments, dry and wetted regions are displayed as white and black, respectively. At the lower flow rates, liquid films are separated and several rivulets are formed. Since the test plate is made of the cast acrylic material, the plate surface is considered to be hydrophobic without liquid absorption. The contact force at the interface between dry and wet regions affects the film flow to resist movement. Thus, the liquid film requires a minimum film thickness to overcome the contact force. At the lower flow rates, the liquid film proceeds toward the thickness increase by forming the rivulet flow and reducing the wetted area fraction. As the flow rates increase, the rivulet flow transits to continuous film flow. The film width also deceases compared to the inlet condition.



(a) Γ=73 g/m/s (b) Γ=125 g/m/s (c) Γ=212 g/m/s (d) Γ=505 g/m/s

Fig. 3. Comparison between experiments and simulations for partially wetted film flow on a vertical plate

The liquid film solver reveals similar results with the partial-wetting experiments. The major discrepancy is observed at the transition region from the rivulet formation to the continuous film flow. There is a strong dependence on the critical thickness (or contact-angle force) which determines the film separation and the wetted area fraction. However, the contact angle is also affected by other unknown parameters such as surface roughness. In the present model, an empirical parameter is used to adjust the film behavior on real planes. In addition, the liquid film model assumes a quadratic velocity profile along the film thickness. The spatial formation of narrow rivulets and oscillating front can perturb this assumption.

4. Conclusions

The liquid film solver implemented in OpenFOAM is validated by simulating falling films on a vertical plate. The simple 1D falling film reveals an oscillating curvature at the front section. The steady-state film velocity and thickness show good agreements with the Nusselt theory. The partially wetted flow is simulated to account for the 2D liquid film phenomena such as wet/dry separation, rivulet formation, isolated wet droplets, etc. The simulation appropriately predicts the formation of the rivulet flow and the reduction of the wetted area fraction. The present liquid film solver will be employed for the steam condensation analysis on the cooling surface in ensuring the structural integrity of the containment.

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REFERENCES

[1] R. O. Gauntt, et al., MELCOR Computer Code Manuals, NUREG/CR-6119, Vol. 1, Rev. 3, SAND2005-5713, 2005.
[2] W. Nusselt, De oberflachenkondensation des waserdampfes, Z Vereines Deutch. Ing., vol. 60, p. 541-546, 569-575, 1916.
[3] P. L. Kapitsa and S. P. Kapitsa, "Wave Flow of Thin Layers of a Viscous Liquid," Zh. Eksp. Teor. Fiz, vol. 18, pp. 3-28, 1948.
[4] H. Brauer, VDI-Forschungshefi 457, Forschung auf dem Gebiete des Ingenieurwesens, vol. 22, 1956.
[5] Ž. Tuković and H. Jasak. Simulation of Thin Liquid Film Flow using OpenFOAM Finite Area Method. Presentation at 4th OpenFOAMWorkshop, Montreal, Canada, 2009.
[6] OpenFOAM Web site, “https://openfoam.org”.
[7] K. Meredith, A. Heather, J. De Vries, and Y. Xin. A Numerical Model for Partially-Wetted Flow of Thin Liquid Films. Computational Methods in Multiphase Flow VI, vol. 70, p.239-250, 2011.