

STUDY OF OPENFOAM VOF METHOD CAPABILITIES FOR NUMERICAL SIMULATION OF DROPLET IMPACT ON THICK LAYER AT LARGE FROUDE NUMBERS

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Introduction

Technical applications

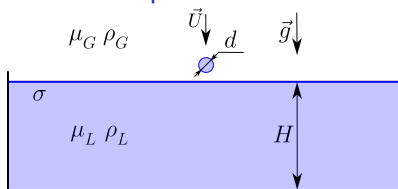
- design of microchips;
- ink-jet printing;
- design of filters;
- internal-combustion engines, etc.



Specifics of model

- strong deformations of the free surface;
- large-scale and small-scale effects in the same case;
- large influence of liquid properties to the solution.

Model setup



Main assumptions

- fluid: incompressible, viscous, isotropic;
- $H \gg d$.

Governing equations:

- continuity equation (for incompressible fluid):

$$\nabla \cdot \mathbf{U} = 0;$$

- Navier — Stokes equations:

$$\frac{\partial \rho \mathbf{U}}{\partial t} + (\rho \mathbf{U} \cdot \nabla) \mathbf{U} = -\nabla p + \nabla \cdot \hat{\tau} + \rho \mathbf{g}.$$

Here:

ρ — density;

μ — dynamic viscosity coefficient;

σ — surface tension coefficient;

\mathbf{U} — velocity; p — pressure;

$\hat{\tau} = \mu(\nabla \mathbf{U} + \nabla \mathbf{U}^T)$ — viscous stress tensor;

\mathbf{g} — gravity forces.

Boundary conditions on the free surface

$$\mathbf{U}_1 = \mathbf{U}_2;$$

$$(\rho_1 - \rho_2)\mathbf{n} + (\hat{\tau}_1 - \hat{\tau}_2) \cdot \mathbf{n} = -\sigma\kappa\mathbf{n}.$$

Dimensionless numbers

- Reynolds number:

$$\text{Re} = \frac{\rho U d}{\mu};$$

- Weber number:

$$\text{We} = \frac{\rho U^2 d}{\sigma};$$

- Froude number:

$$\text{Fr} = \frac{U^2}{gd}.$$

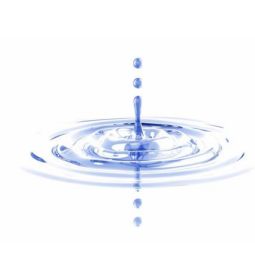
Large-scale effects



Crater



Crown



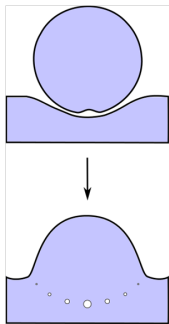
High-speed jet

Instabilities

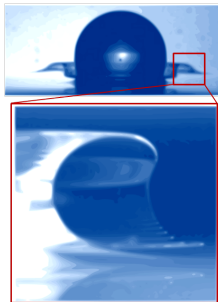
- spikes on the crown: Calvin — Helmholtz instability^a;
- drops on the jet: Rayleigh — Plateau instability.

^aS.S. Yoon, R.A. Jepsen, S.C. James, Jie Liu, G. Aguilar. Are Drop-Impact Phenomena Described by Rayleigh-Taylor or Kelvin-Helmholtz Theory? // *Drying Technology*. 2009. Vol. 27. P. 316–321.

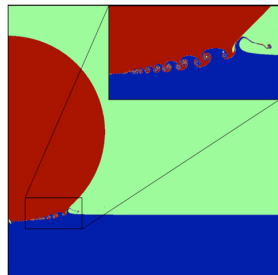
Small-scale effects



Air entrapment¹



Ejecta sheet²



Vorticity structures³

¹Tran T., de Maleprade H., Sun C., Lohse D. Air entrainment during impact of droplets on liquid surfaces // *JFM Rapids*. 2013. Vol. 726.

²Deegan R.D., Brunet P., Eggers J. Complexities of splashing // *Nonlinearity*. 2008. Vol. 21, iss. 1.

³Thoraval M.-J., Takehara K., Goji Etoh T., Popinet S., Ray P., Josserand C., Zaleski S., Thoroddsen S.T. von Kármán Vortex Street within an Impacting Drop // *Phys. Rev. Lett.* 2012. V. 108.

Regime maps

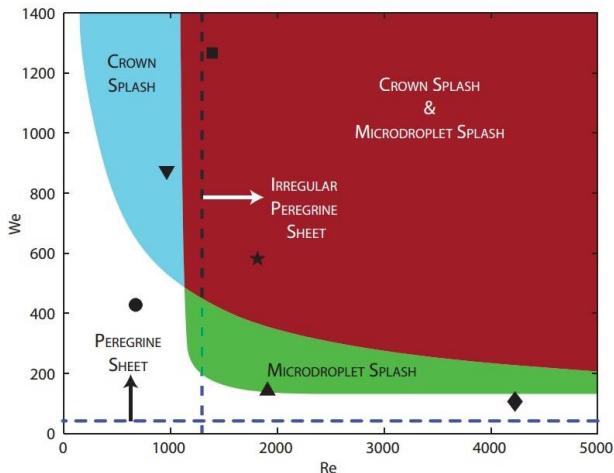
Crown splash⁴



Microdroplet splash

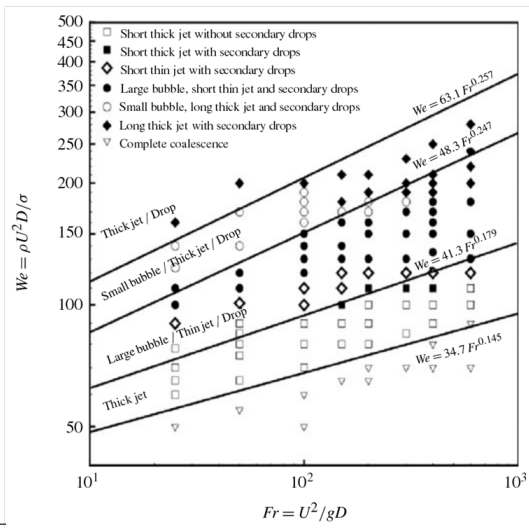
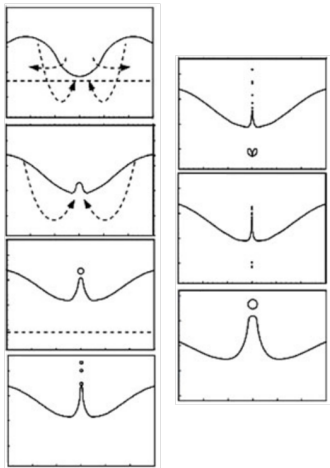


Crown splash



⁴Deegan R.D., Brunet P., Eggers J. Complexities of splashing // Nonlinearity. 2008. Vol. 21, iss. 1.

Regime maps

High-speed jet⁵

⁵Ray B., Biswas G., Sharma A. Regimes during liquid drop impact on a liquid pool // J. Fluid Mech. 2015. Vol. 768. P. 495–522.

The main goal, tasks and tools

Now

- small range of dimensionless criteria;
- empirical curves are the power functions, but saturation is existed.

The main goal

To build the regime maps for large Froude numbers (more than 10^5).
Practically — very small droplets ($d \approx 1 \text{ um}$) with very high impact velocity (more than 100 m/s).

The main tool — the `interFoam` solver.

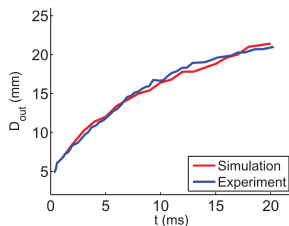
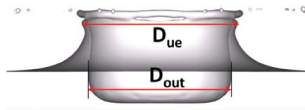
Steps of investigation

- find an information about validation in literature;
- make some validation tests by hands;
- make a series of computations to build the sought-for regime maps.

Literature information

Good agreement with experiments:

- Droplet impact and crown propagation⁶
- 2D standing capillary wave⁶
- Rayleigh breakup of a laminar liquid jet⁶
- Retraction of a liquid column⁶
- Kelvin — Helmholtz instability⁷



⁶S.S. Deshpande, L. Anumolu and M.F. Trujillo, Evaluating the performance of the two-phase flow solver interFoam, *Comp. science and discovery*, 5(1), 2012.

⁷K. Wedolowski, K. Bajer and K. Kwiatkowski, Analysis and modelling of the effective reaction rate in a developing mixing layer, *Journal of Physics*, 318(9), 2011.

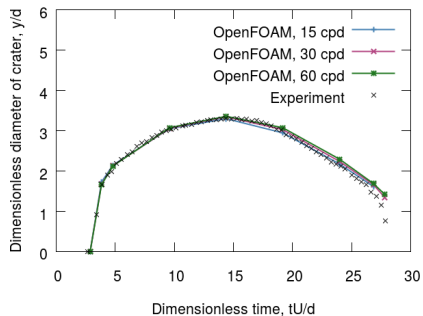
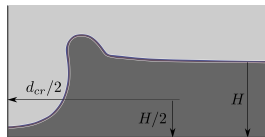
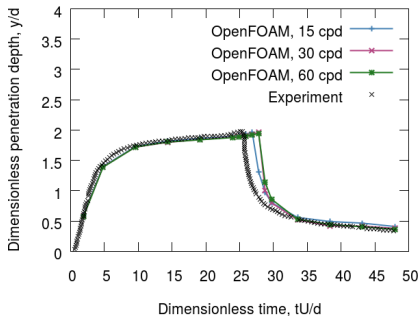
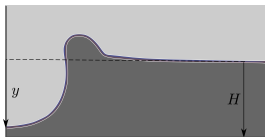
Hands-on validation: large-scale effects⁸

Table: Input data for validation test of large-scale effects

| Property | Value |
|---|--|
| Droplet diameter, d | 2.67 mm |
| Impact velocity, U | 2.56 m/s |
| Depth of the liquid layer, H | 5.34 mm |
| Density of liquid, ρ_f | 1179 kg/m ³ |
| Dynamic viscosity of liquid, μ_f | 18.57×10^{-3} Ns/m ² |
| Density of air, ρ_a | 1.204 kg/m ³ |
| Dynamic viscosity of air, μ_a | 1.9×10^{-3} Ns/m ² |
| Surface tension coefficient, σ | 0.063 N/m |
| Characterize size of the flow domain, L | 45 mm |
| Max mesh refinement | 60 cpd (cells per diameter) |
| CFL | 0.2 |

⁸Berberović E., van Hinsberg N.P., Jakirlić S., Roisman I.V., Tropea C. Drop impact onto a liquid layer of finite thickness: Dynamics of the cavity evolution // Physical Review. 2009. Vol. 79. P. 1–15.

Hands-on validation: large-scale effects⁹



⁹Berberović E., van Hinsberg N.P., Jakirlić S., Roisman I.V., Tropea C. Drop impact onto a liquid layer of finite thickness: Dynamics of the cavity evolution // Physical Review. 2009. Vol. 79. P. 1–15.

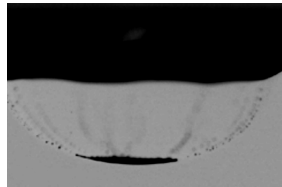
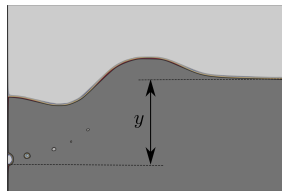
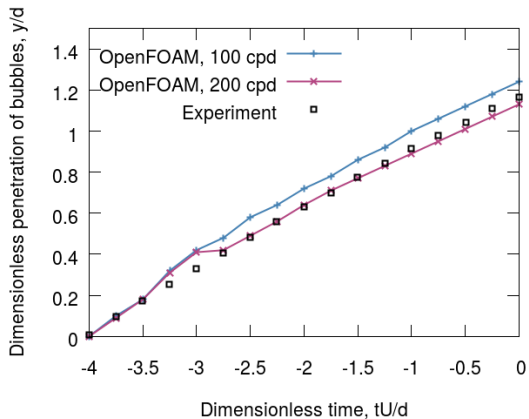
Hands-on validation: small-scale effects¹⁰

Table: Input data for validation test of large-scale effects

| Property | Value |
|---|--|
| Droplet diameter, d | 1.9 mm |
| Impact velocity, U | 0.55 m/s |
| Depth of the liquid layer, H | 10 mm |
| Density of liquid, ρ_f | 953 kg/m ³ |
| Dynamic viscosity of liquid, μ_f | 0.1906 Ns/m ² |
| Density of air, ρ_a | 1.204 kg/m ³ |
| Dynamic viscosity of air, μ_a | 1.9×10^{-3} Ns/m ² |
| Surface tension coefficient, σ | 0.0197 N/m |
| Characterize size of the flow domain, L | 45 mm |
| Max mesh refinement | 200 cpd (cells per diameter) |
| CFL | 0.2 |

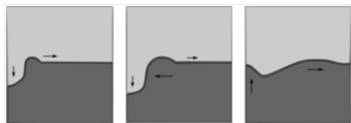
¹⁰Tran T., de Maleprade H., Sun C., Lohse D. Air entrainment during impact of droplets on liquid surfaces // JFM Rapids. 2013. Vol. 726. P. 1–11.

Hands-on validation: small-scale effects¹¹



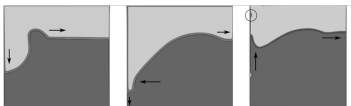
¹¹Tran T., de Maleprade H., Sun C., Lohse D. Air entrainment during impact of droplets on liquid surfaces // JFM Rapids. 2013. Vol. 726. P. 1–11.

Consequence of effects: fixed $Re=1200$, increasing We



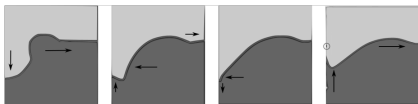
$We=94.5$

Complete coalescence of crater: the crater bottom gently rises, the jet is like a hill. No secondary drops.



$We=189$

The small drops appear: the crater bottom descends, the walls of the crater are hit each other and entrap the air bubble.

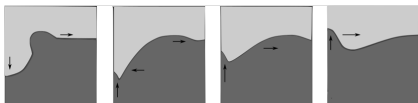


$We=378$

The diameter of secondary drops is decreases: the crater bottom descends till the some limit depth and begin rise up.

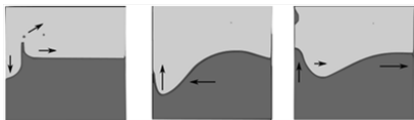
Consequence of effects: fixed $Re=1200$, increasing We

$We=756$



The secondary drops effect disappears: the crater bottom rises to the some max value, and the crater walls can't hit each other.

$We=1890$



For small Re : the jet becomes longer, the big secondary drop can formed on the top of jet.

For large Re (more than 1000): the secondary drops can tearing from the crown, and the sequence of the regimes for jet repeats if We increasing.

Liquid-gas density ratio

Additional parameter

If the pressure of external gas decreases the instabilities on the crown are suppressed.^a

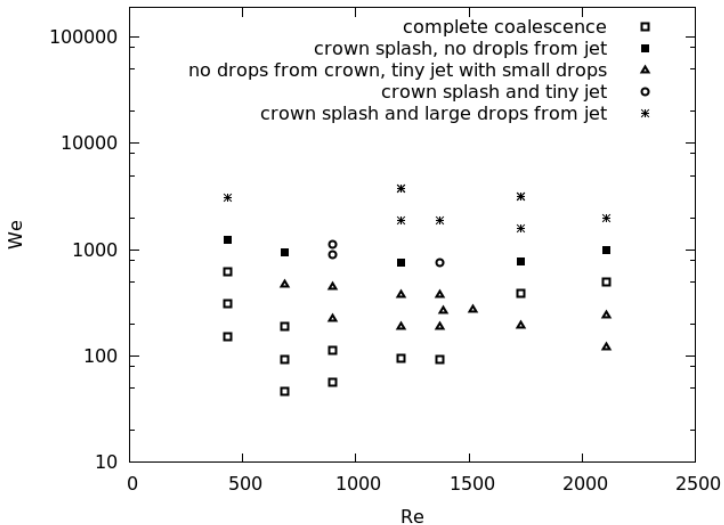
^aLei Xu, Wendy W. Zhang, Sidney R. Nagel. Drop Splashing on a Dry Smooth Surface // Physical Review Letters. 2005. Vol. 94, iss. 48. P. 1–4.

Incompressible fluid

For incompressible fluid we use the gradient of pressure, not the absolute value of pressure.

Consequently, it is possible to change the external pressure in the computations artificially by changing of the liquid/gas density ratio

$$R_{GL} = \frac{\rho_G}{\rho_L}.$$

Regime maps: $R_{GL} \approx 10^{-3}$ 

Conclusions

- The review of different researches about the droplet impact to the liquid layer (as deep pool as the tiny layer) has been done.
- The validation of applicability of OpenFOAM to solve such cases has been done by two ways: analyse of the articles and the hands-on validation.
- The first results of the research of the droplet impact to the liquid layer were created. The regime maps were drawn according to the liquid/density ratio.