SPHERIC International Workshop, 17-20 Oct. 2017, Beijing, China

SPH simulation of drop impact on a hot wall with vaporization effects

Xiufeng YANG, Iowa State University, USA
Song-Charng KONG, Iowa State University, USA
Moubin LIU, Peking University, China

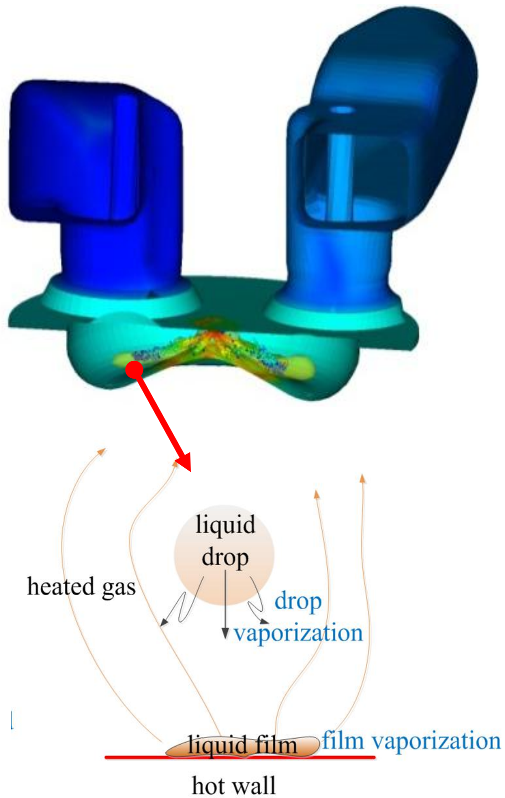
Acknowledgement: Ford Research and Innovation Center

Outline

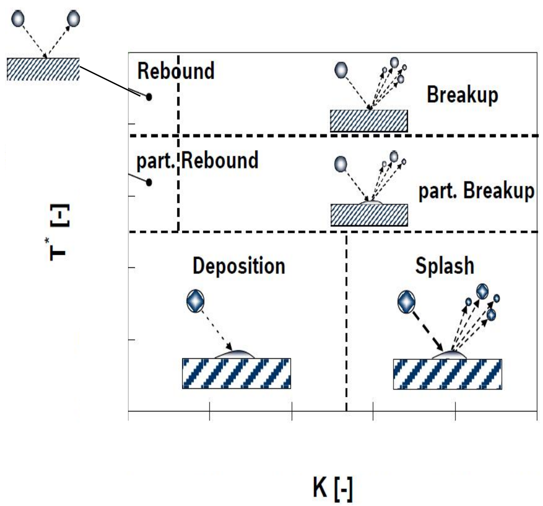
- Background
- SPH method for vaporization
  - Governing equations
  - Particle splitting and merging
- Validation
  - Stefan problem
  - Vaporization of a static drop
- Drop impact on a wall at different temperatures
  - Different outcomes
- Summary

Background

- Drop-wall interactions are common and important in industrial applications.
- For IC engines, the fuel drops may impact on solid surfaces.
- Engineering models of drop-wall interaction use empirical formulations.

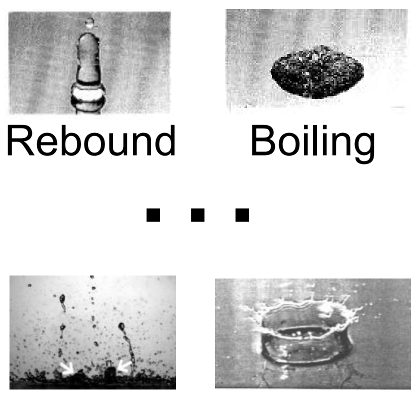


Engineering models



We < 80, rebound

We > 80, wall jet



Drop on wet surface

SPH method

- Governing equations

$$\frac{d\rho}{dt} = -\rho\nabla\cdot\boldsymbol{u} + \dot{m}'''$$

Vaporization

$$\frac{d\boldsymbol{u}}{dt} = \boldsymbol{g} - \frac{1}{\rho}\nabla p + \frac{\mu}{\rho}\nabla^2\boldsymbol{u}$$

$$\frac{dT}{dt} = \frac{1}{\rho C_p}\nabla\cdot(\kappa\nabla T) - \frac{h_v}{\rho C_p}\dot{m}'''$$

$$\frac{dY}{dt} = \frac{\nabla\cdot(\rho D\nabla Y)}{\rho}$$

$$p = c^2(\rho - \rho_r) + p_r$$

Continuity equation of vapor species

Y is vapor mass fraction

Mass evaporation rate

$$\dot{m} \equiv \frac{dm}{dt} = \frac{V\nabla\cdot(\rho D\nabla Y)}{1-Y}$$

$$\dot{m}''' = \frac{\dot{m}}{V} = \frac{\nabla\cdot(\rho D\nabla Y)}{1-Y}$$

Saturated vapor mass fraction

$$Y_s = \frac{X_s M_v}{(1-X_s)M_g + X_s M_v}$$

$$X_s = \frac{p_s}{p_{ag}} = \exp\left[-\frac{h_v M_v}{R}\left(\frac{1}{T_s} - \frac{1}{T_B}\right)\right]$$

- SPH formulas

$$\frac{d\rho_a}{dt} = \sum_b m_b\left(\boldsymbol{u}_a - \boldsymbol{u}_b\right)\cdot\nabla_a W_{ab} + \dot{m}_{\mathrm{g}}'''$$

Valid for gas particles at interface

$$\frac{d\boldsymbol{u}_a}{dt} = \boldsymbol{g} - \sum_b m_b\left(\frac{p_a + p_b}{\rho_a\rho_b} + \Pi_{ab}\right)\nabla_a W_{ab} + \sum_b \frac{m_b(\mu_a+\mu_b)(\boldsymbol{r}_a-\boldsymbol{r}_b)\cdot\nabla_a W_{ab}}{\rho_a\rho_b(r_{ab}^2+\eta)}(\boldsymbol{u}_a-\boldsymbol{u}_b)$$

$$\frac{dT_a}{dt} = \frac{1}{C_p}\sum_b \frac{m_b(\kappa_a+\kappa_b)(\boldsymbol{r}_a-\boldsymbol{r}_b)\cdot\nabla_a W_{ab}}{\rho_a\rho_b(r_{ab}^2+\eta)}(T_a-T_b) - \frac{h_v}{\rho C_p}\dot{m}_{\mathrm{g}}'''$$

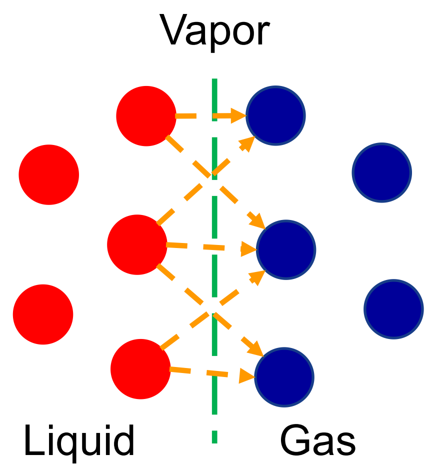
Valid for liquid particles at interface

$$\frac{dY_a}{dt} = \sum_b \frac{m_b(\rho_a D_a + \rho_b D_b)(\boldsymbol{r}_a-\boldsymbol{r}_b)\cdot\nabla_a W_{ab}}{\rho_a\rho_b(r_{ab}^2+\eta)}(Y_a-Y_b)$$

$$\dot{m}_{\mathrm{g}}''' = \sum_{\mathrm{l}} \frac{2\rho_{\mathrm{g}} m_{\mathrm{l}} D_{\mathrm{g}}(\boldsymbol{r}_{\mathrm{g}}-\boldsymbol{r}_{\mathrm{l}})\cdot\nabla_{\mathrm{g}} W_{\mathrm{gl}}}{\rho_{\mathrm{l}}(r_{\mathrm{gl}}^2+\eta)(1-Y_{\mathrm{g}})}(Y_{\mathrm{g}}-Y_{\mathrm{l}})$$

$$\frac{dm_{\mathrm{g}}}{dt} = \sum_{\mathrm{l}} \frac{2m_{\mathrm{g}} m_{\mathrm{l}} D_{\mathrm{g}}(\boldsymbol{r}_{\mathrm{g}}-\boldsymbol{r}_{\mathrm{l}})\cdot\nabla_{\mathrm{g}} W_{\mathrm{gl}}}{\rho_{\mathrm{l}}(r_{\mathrm{gl}}^2+\eta)(1-Y_{\mathrm{g}})}(Y_{\mathrm{g}}-Y_{\mathrm{l}})$$

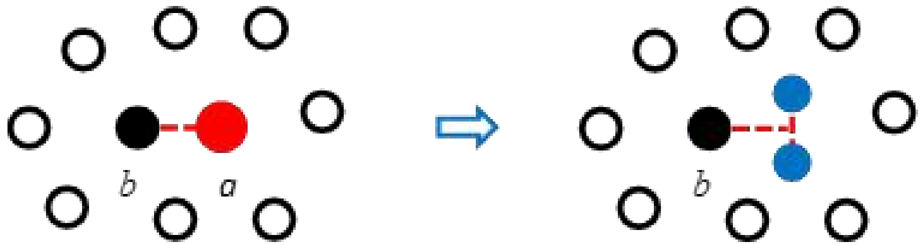
$$\frac{dm_{\mathrm{l}}}{dt} = -\sum_{\mathrm{g}} \frac{2m_{\mathrm{g}} m_{\mathrm{l}} D_{\mathrm{g}}(\boldsymbol{r}_{\mathrm{g}}-\boldsymbol{r}_{\mathrm{l}})\cdot\nabla_{\mathrm{g}} W_{\mathrm{gl}}}{\rho_{\mathrm{l}}(r_{\mathrm{gl}}^2+\eta)(1-Y_{\mathrm{g}})}(Y_{\mathrm{g}}-Y_{\mathrm{l}})$$



SPH method

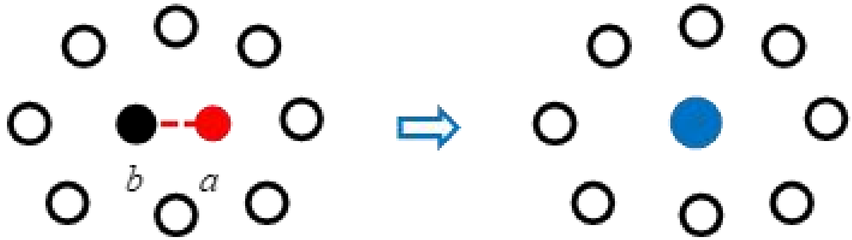
- Particle splitting
  - Particle *a* will be split into two smaller particles when the following condition is satisfied.

$$\frac{m_a}{m_r} > \gamma_{\max}$$



- Particle merging
  - Particle *a* will merge with its nearest particle *b* when the following condition is satisfied.

$$\frac{m_a}{m_r} < \gamma_{\min}$$



Physical properties of fluids

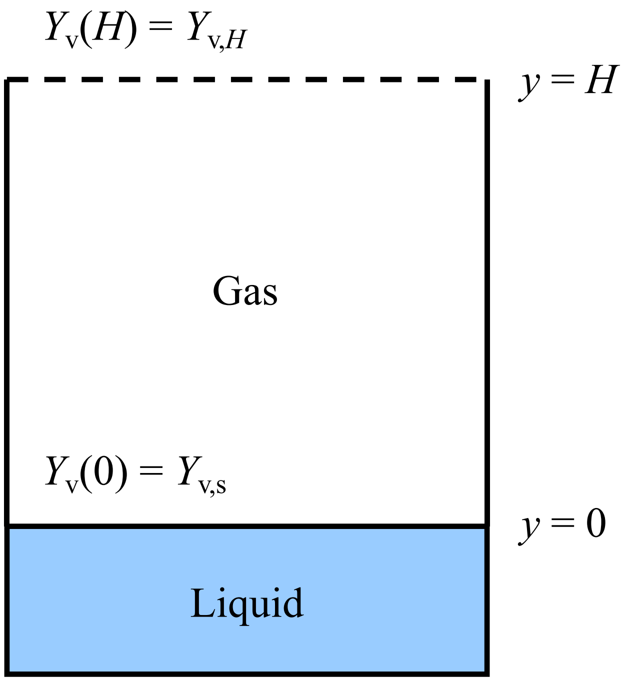
- Physical properties of the liquid and gas phases

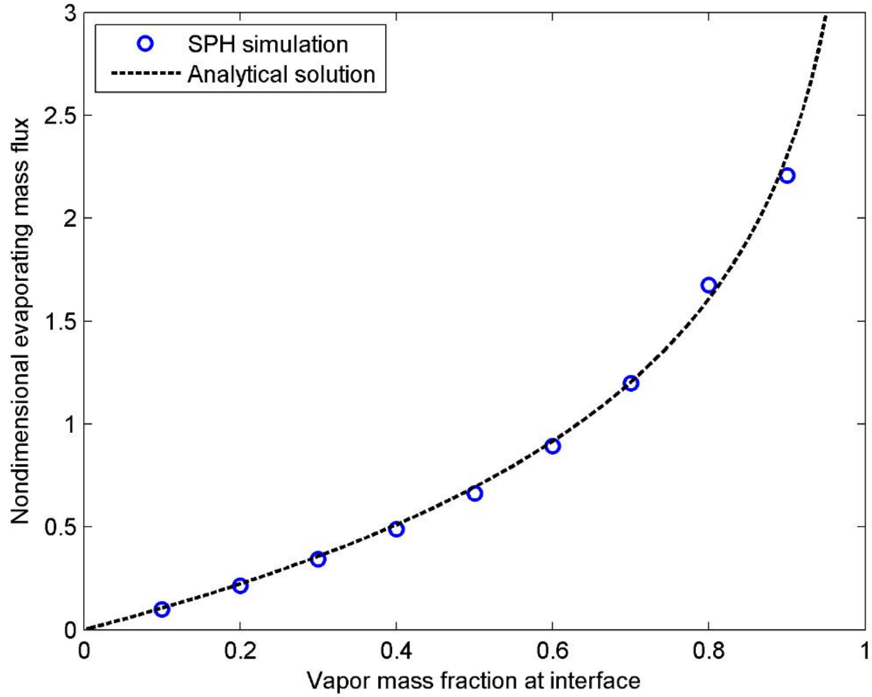
	ρ (kg/m^3)	μ (kg/m/s)	κ (W/m/K)	C_p (J/kg/K)	M (kg/mol)	h_v (J/kg)	T_B (K)	D_v (m^2/s)
Air	1.2	2×10^{-5}	0.046	1000	0.029			2×10^{-5}
Water	1000	1×10^{-3}	0.6	4180	0.018	2.3×10^{6}	373	
Nitrogen	1.25	3×10^{-5}	0.026	1040	0.028			1×10^{-5}
n-Heptane	684	4×10^{-4}	0.12	2220	0.1	3.3×10^{5}	372	
Air	1.2	2×10^{-5}	0.046	1000	0.029			9×10^{-6}
iso-Octane	692	4×10^{-4}	0.1	2100	0.114	3.1×10^{5}	372	

Validation

- Stefan problem

$$\dot{m}''_{\mathrm{v}} = \frac{\rho D_{\mathrm{v}}}{H} \ln\left(\frac{1 - Y_{\mathrm{v},H}}{1 - Y_{\mathrm{v},s}}\right)$$



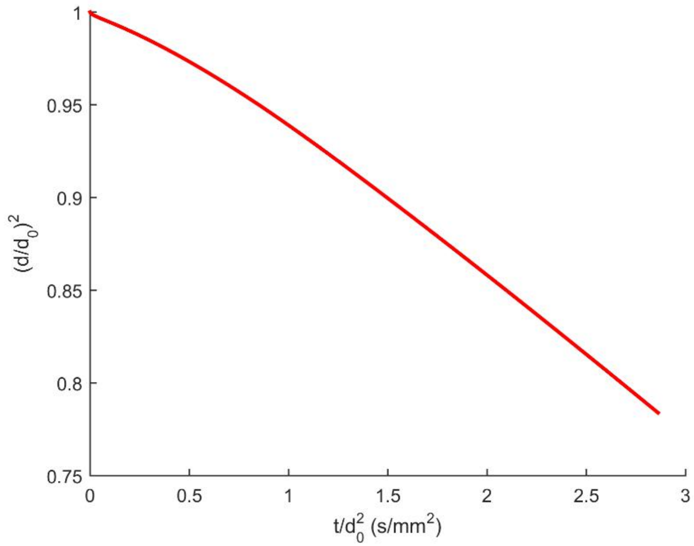


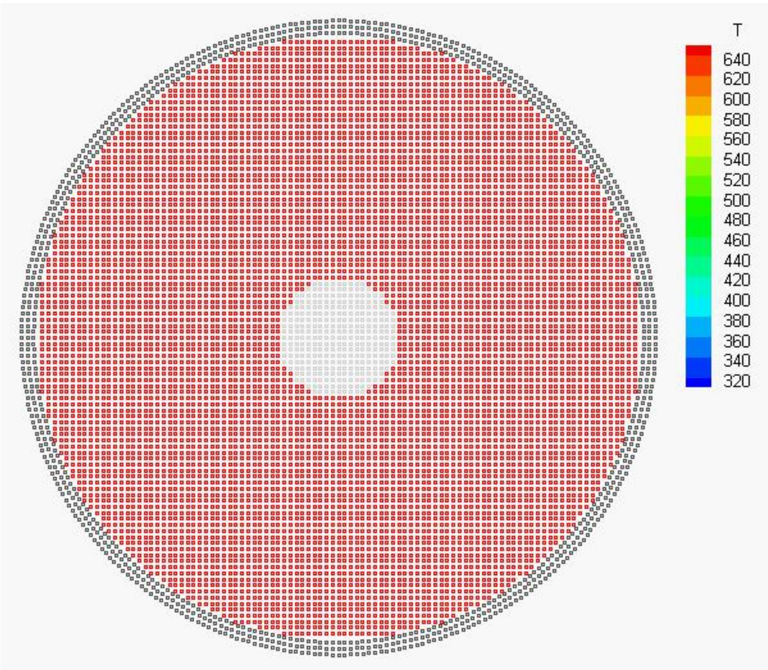
Validation

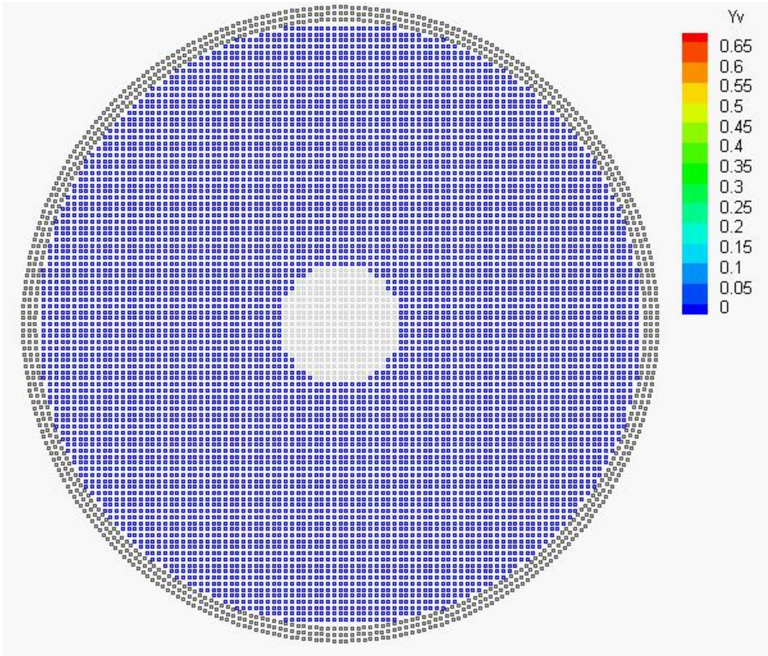
- Vaporization of a static drop

$$\left(2\ln\frac{r_L}{r_s}+1\right)\left(\frac{r_s}{r_0}\right)^2=1-4K\frac{t}{r_0^2}$$

$$K=\frac{\rho_g D_v}{\rho_l}\ln\frac{1-Y_{v,L}}{1-Y_{v,s}}$$

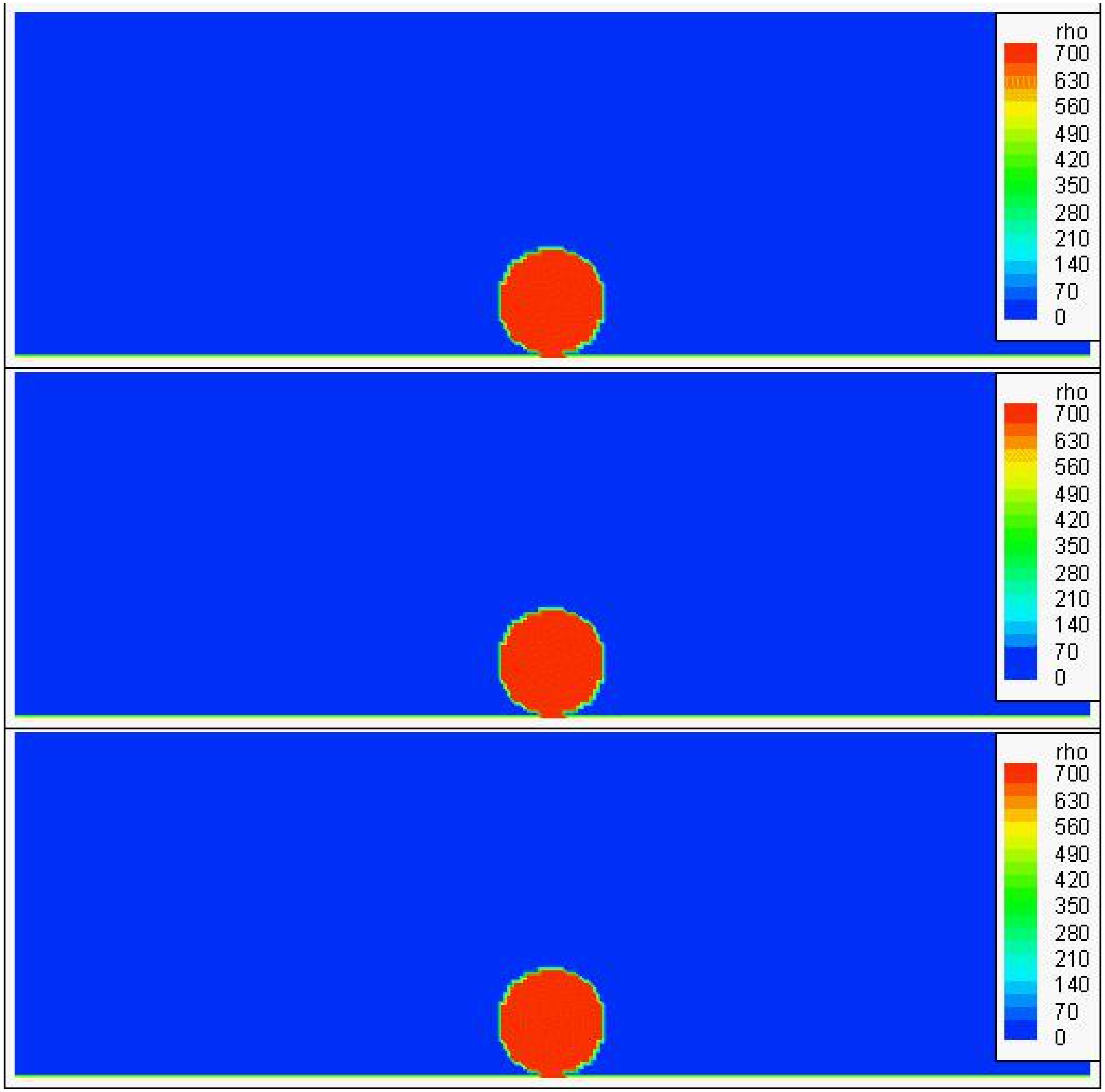






Drop impact on a surface

- Tw = 50 ºC
- D = 50 μm
- U = 2 m/s
- Deposition
- U = 5 m/s
- Contact-splash
- U = 50 m/s
- Contact-breakup



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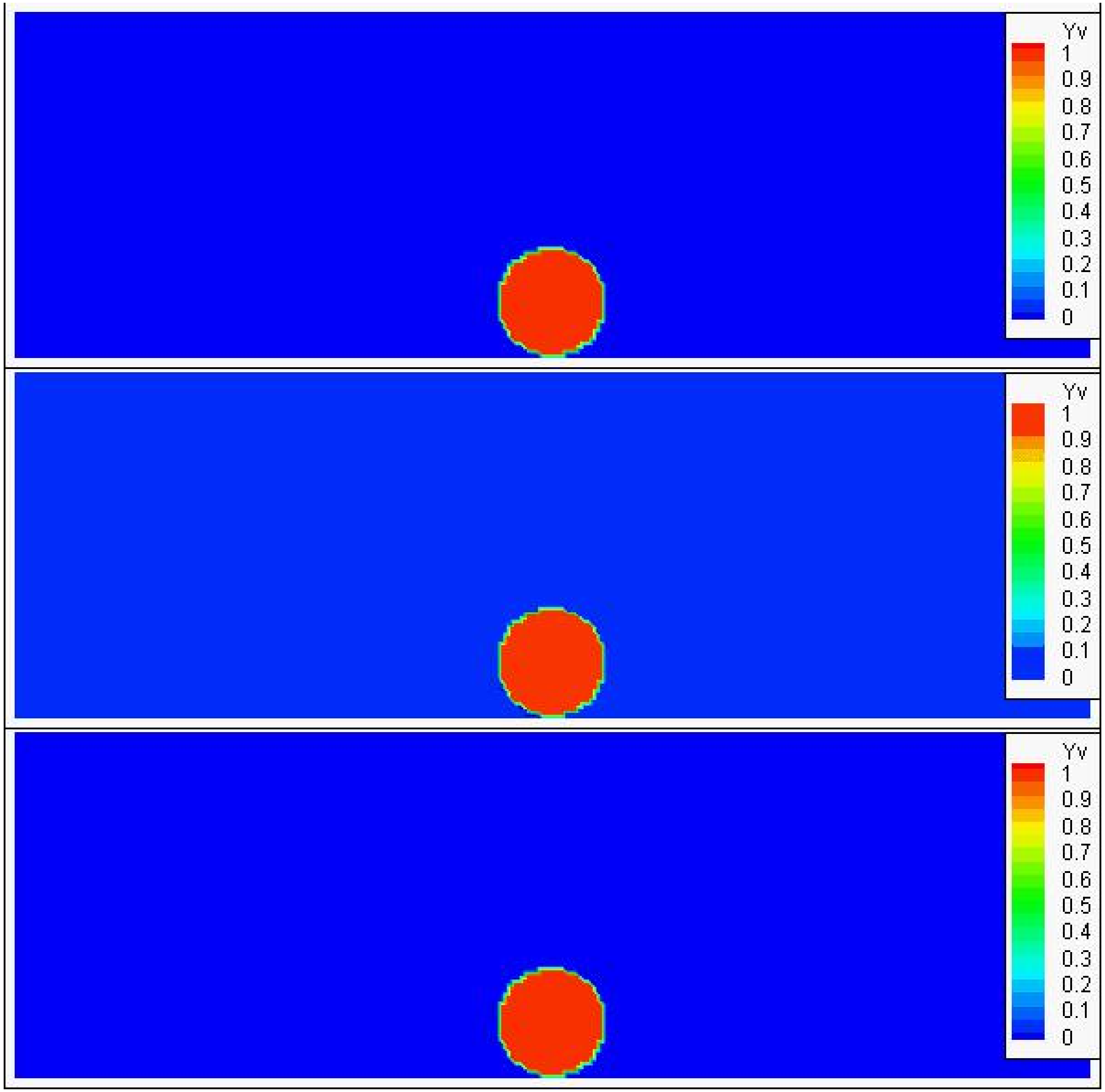
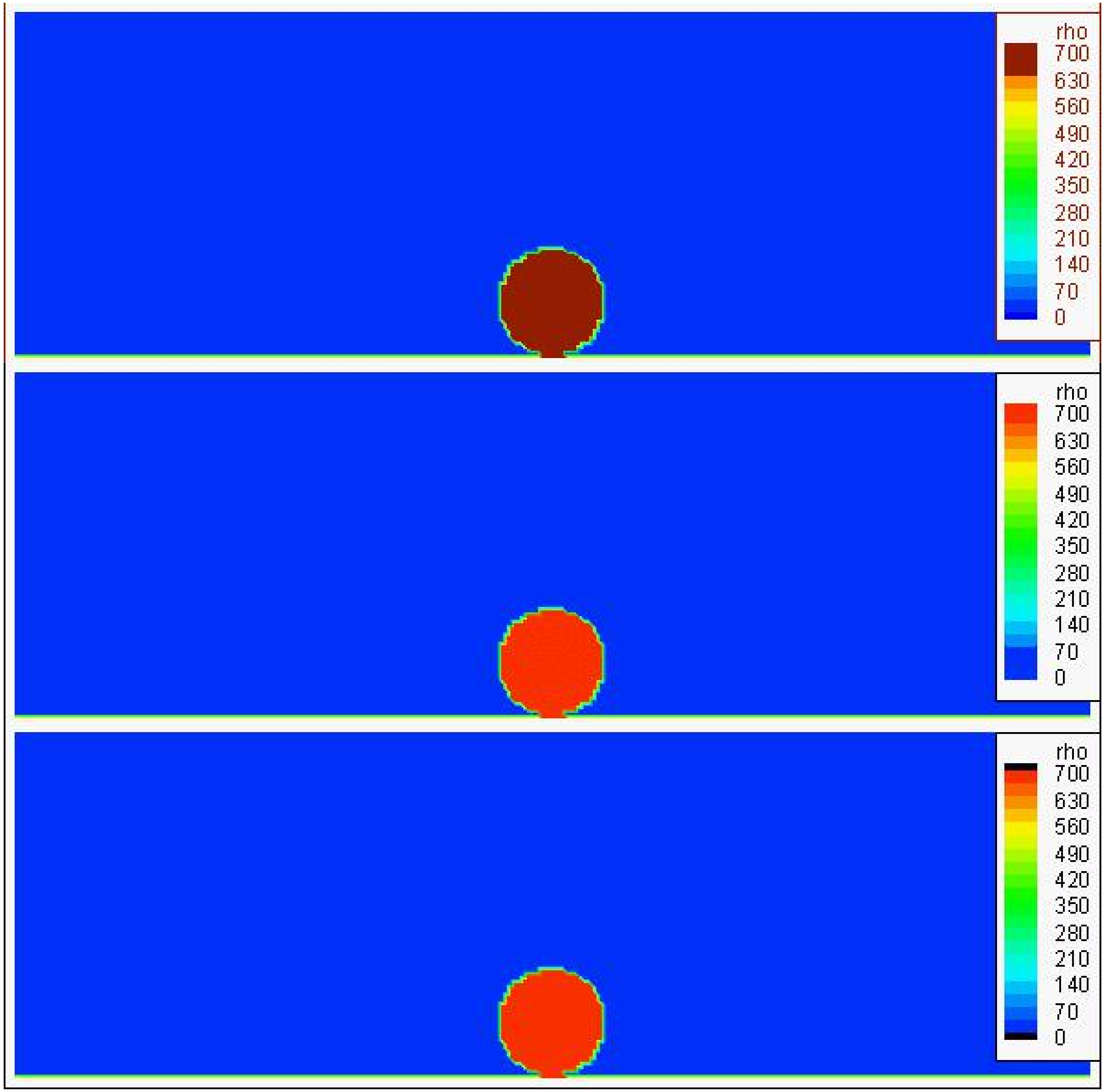


Drop impact on a hot surface

- Tw = 250 ºC
- D = 50 μm
- U = 1 m/s
- Rebound

- U = 5 m/s
- Film-splash

- U = 50 m/s
- Film-breakup



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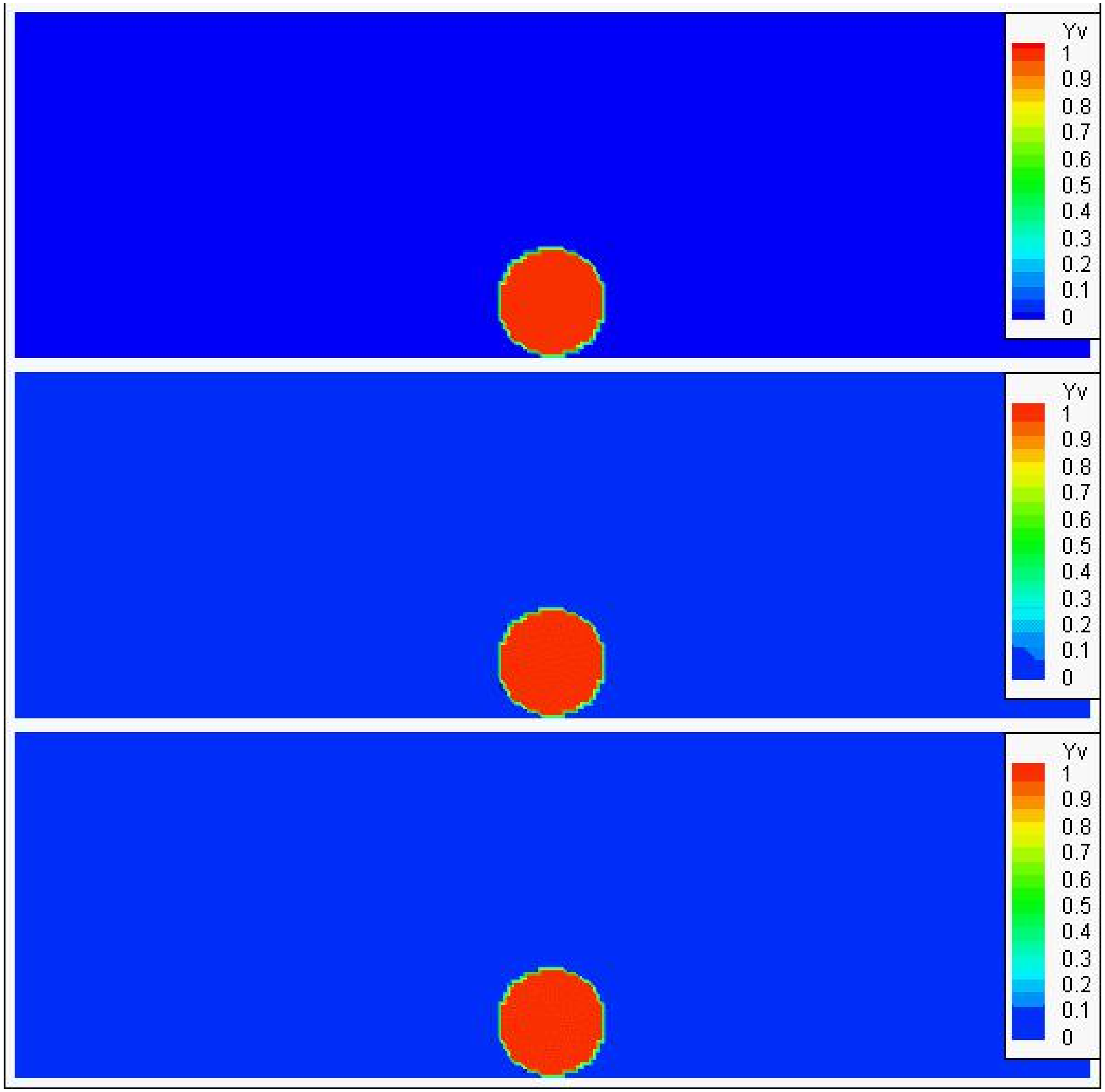
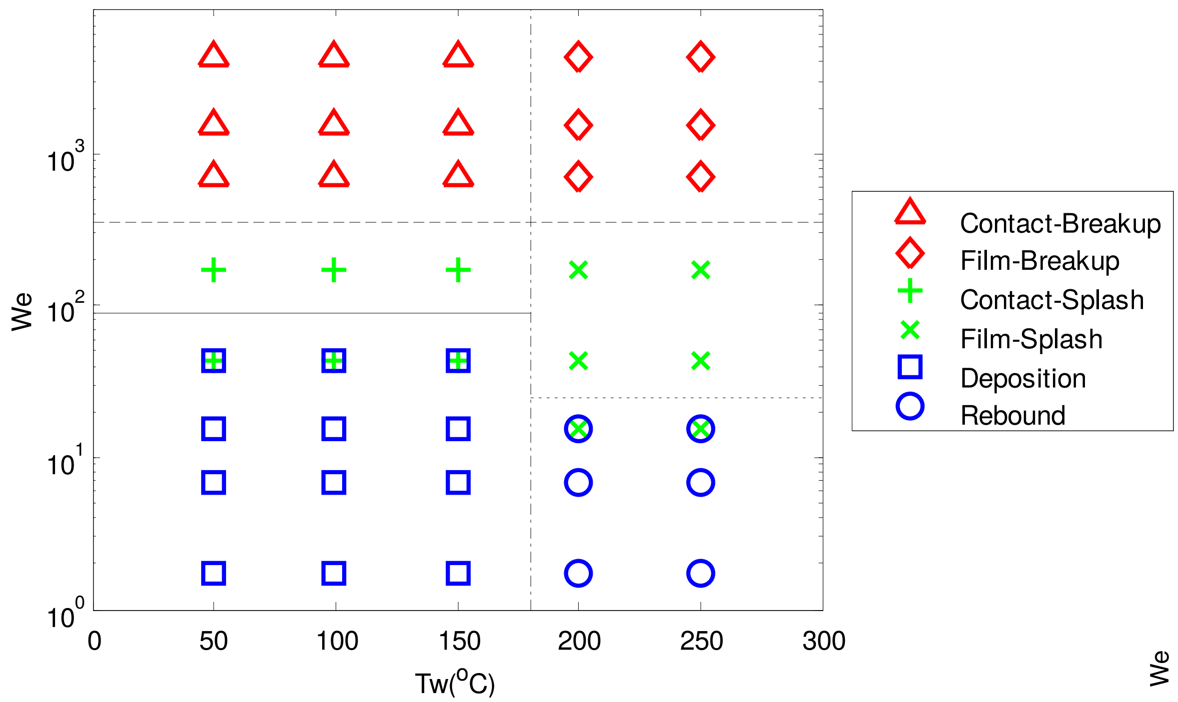


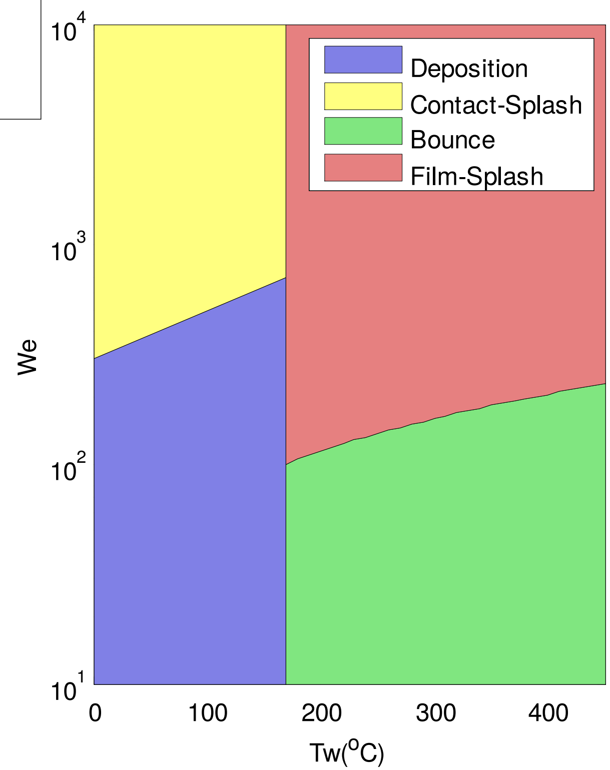
Impact regimes



SPH simulation of iso-octane drops

Experiment of ethanol drops

(Staat, et al. 2015, JFM)



Summary

- An SPH method for evaporating flows was presented.
- The SPH method was validated by two numerical examples.
- The SPH method was applied to study drop impact on a heated surface at different temperatures.
- Different outcomes of drop-wall interaction were obtained, such as deposition, splash, breakup, and Leidenfrost phenomenon.