Laboratoire d'Énergétique et de Mécanique
Théorique et Appliquée

Effect of the vapor flow on the drop spreading in the Leidenfrost regime

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Institut Jean le Rond d'Alembert, Paris 5, 2 Octobre 2014

General context

Spray/wall interactions: Collision of droplets onto heated wall

Direct injection engines

Spray cooling

Heat treatment in the metal processing industry

Cooling of a steel band by water sprays
in the hot rolling process

French ANR program IDHEAS in cooperation with Arcelor-Mittal

Impact parameters

Impact dynamical parameters (case of a perfectly flat substrate)

$$We = \frac{\rho_l u_0^2 d}{\sigma} \qquad Re = \frac{\rho_l u_0 d}{\mu_l} \qquad Oh = \frac{\sqrt{We}}{Re}$$

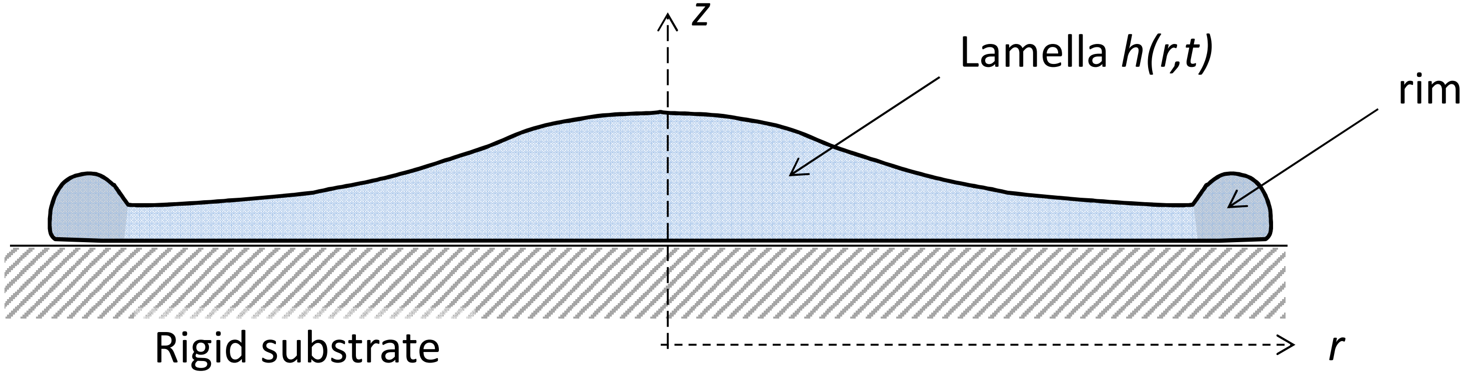
+ Thermal parameters

Many properties of the impacts in the Leidenfrost regime are function of We:

Contact time (t_c)	Biance et al., JFM, 2006. Hatta et al., Journal of Fluids Engineering, 1997.
Spreading time ($t_{x,max}$)	Hatta et al., Journal of Fluids Engineering, 1997. Biance et al., PoF, 2011.
Onset of splashing	Rosa et al., ICLASS, 2006. Castanet et al., IJHMT, 2010.
Leidenfrost temperature (T_{Leid})	Bernardin and Mudawar, Journal of Heat Transfer, 2004. Yao and Cai, Experimental Thermal and Fluid Science, 1988.
Maximum spreading diameter (β_{max})	Karl and Frohn, PoF,2000. Hatta et al., Journal of Fluids Engineering,1997. Tran et al., PRL, 2012.
Coefficient of restitution (COR)	Karl and Frohn, PoF, 2000. Biance et al., JFM, 2006.

What about the viscosity?

Flow inside the lamella



Asymptotic remote solution (Yarin and Weiss 1995, Roisman et al., 2009)

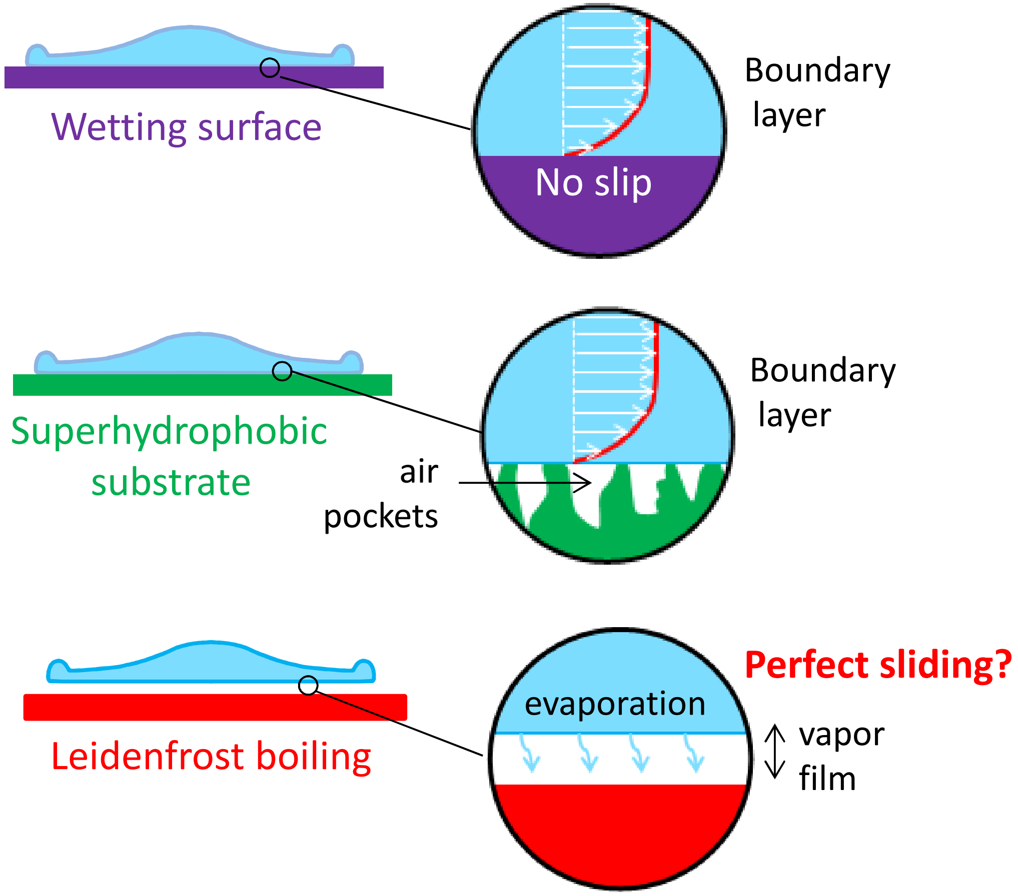
Velocity field: $u_r = \frac{r^*}{t^* + \tau} u_0, \qquad u_z = -\frac{2z^*}{t^* + \tau} u_0$ (inviscid solution)

Lamella thickness: $\frac{h}{d_0} = \frac{\eta}{\left(t^* + \tau\right)^2} \exp\left(-\frac{6\eta r^{*2}}{\left(t^* + \tau\right)^2} \right)$ with $\eta = 0.39, \tau = 0.25$

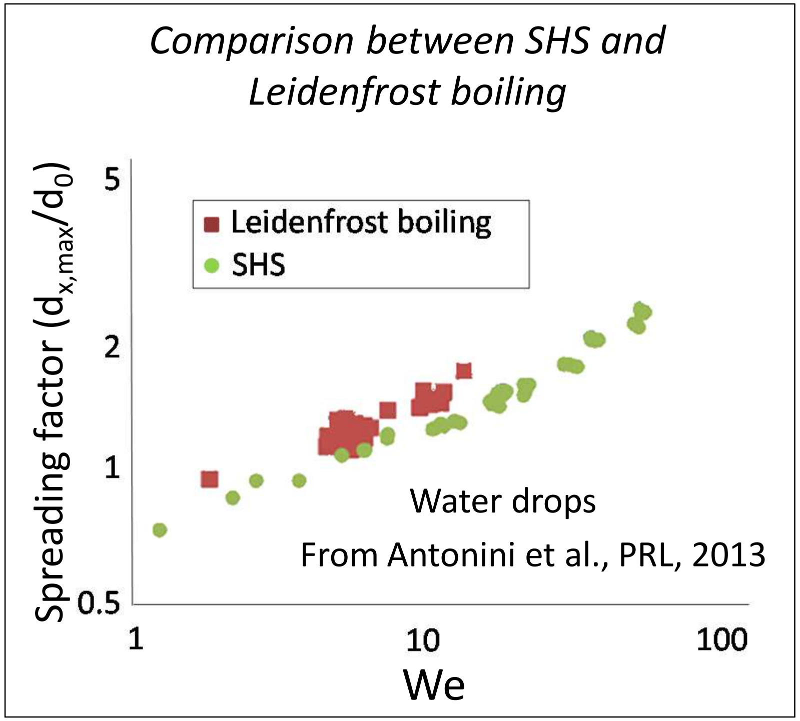
$$r^* = \frac{r}{d_0}, z^* = \frac{z}{d_0} \text{ and } t^* = \frac{t\,u_0}{d_0}$$

Valid at high Reynolds and Weber numbers (typically *Re*>25) and *t**>0,5

Viscous dissipation



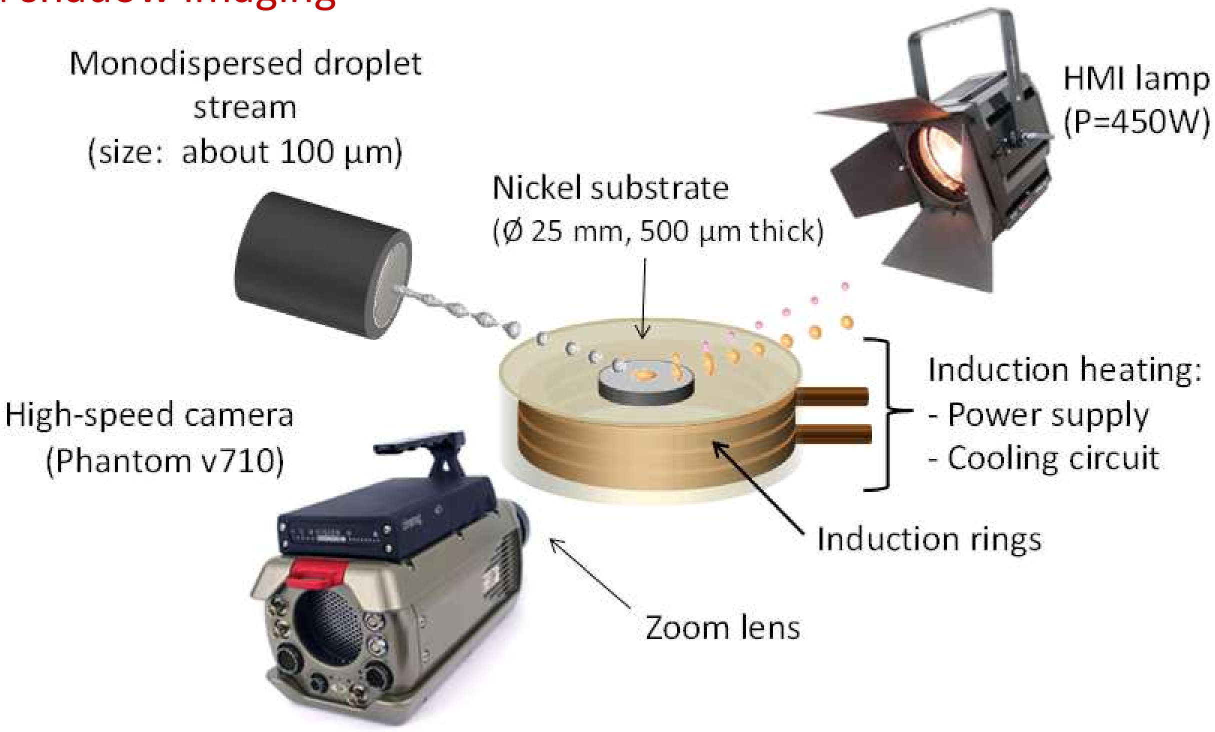
Mechanisms for the frictions at the bottom edge of the droplet


Comparison between SHS and Leidenfrost boiling

From Antonini et al., PRL, 2013

Experimental configuration

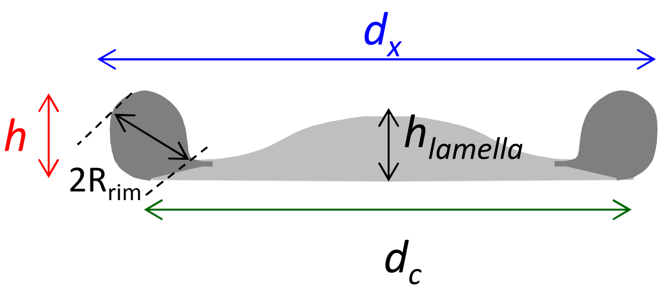
- High-speed shadow imaging

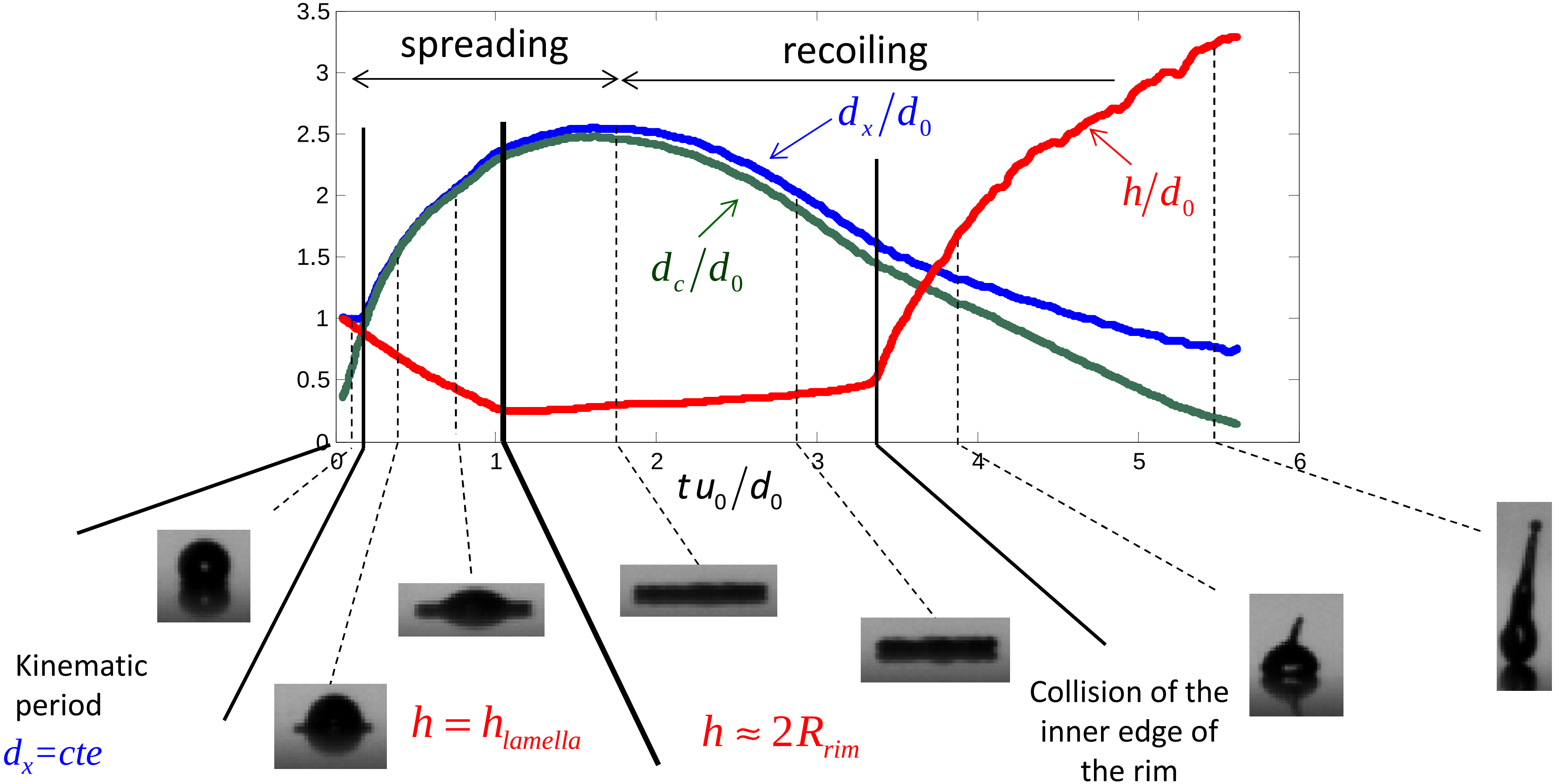


- Investigated conditions

	$d_0\ (\mu m)$	$U_0\ (m/s)$	We	Re	Oh
Water	101-163	1.57 - 6.10	4 - 52	175 - 810	9.85e-3
Ethanol	109-139	0.84 - 3.10	3 – 40	71 – 256	2.5e-2
Water 65% -glycerol 35%	160-164	1.3 - 5	4 – 66	65 – 225	3.16e-2
Water 56% -glycerol 44%	145-154	1 - 4.5	3 – 50	34 – 140	5.02e-2
Water 50% -glycerol 50%	114-129	2 - 6.7	9 – 88	38 – 111	8.22e-2
Water 40% -glycerol 60%	170-200	1 - 5	3 – 86	15 – 78	1.19e-1
Water 35% -glycerol 65%	98-159	3 – 7.7	15 – 152	17 – 67	1.93e-1
Water 30% -glycerol 70%	230-297	1.8 – 5.5	14 - 160	17 – 63	2.16e-1

General phenomena





Kinematic period

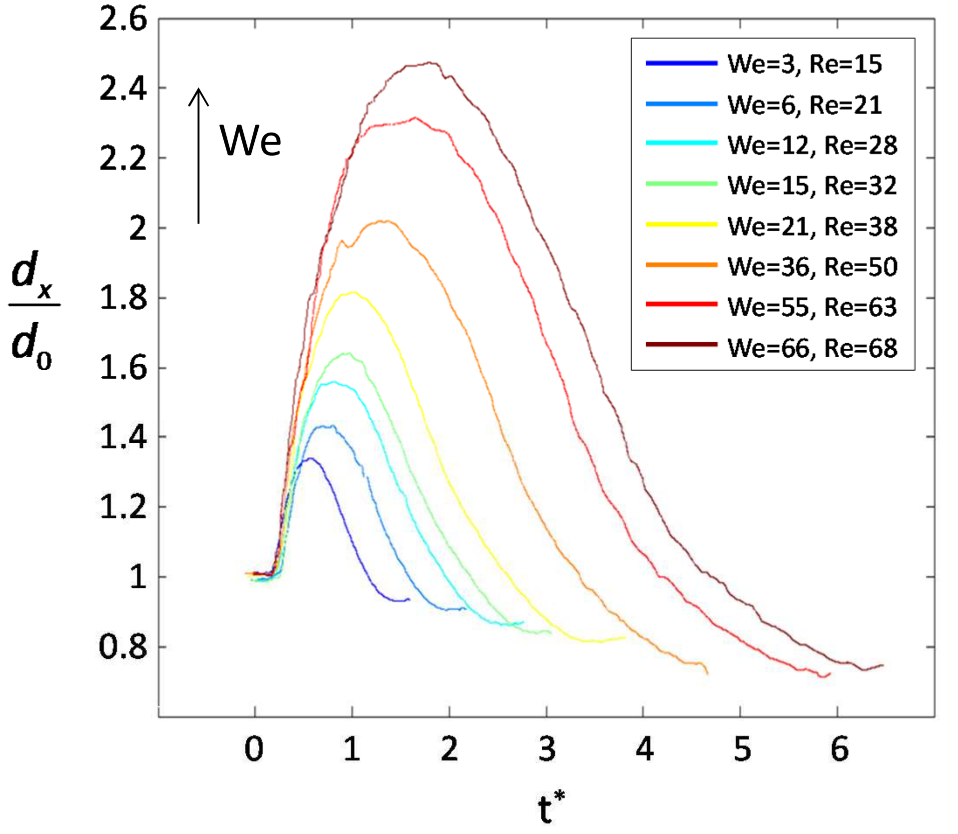
d_x=cte

$h = h_{lamella}$

$h \approx 2R_{rim}$

Collision of the inner edge of the rim

Effect of the Weber number

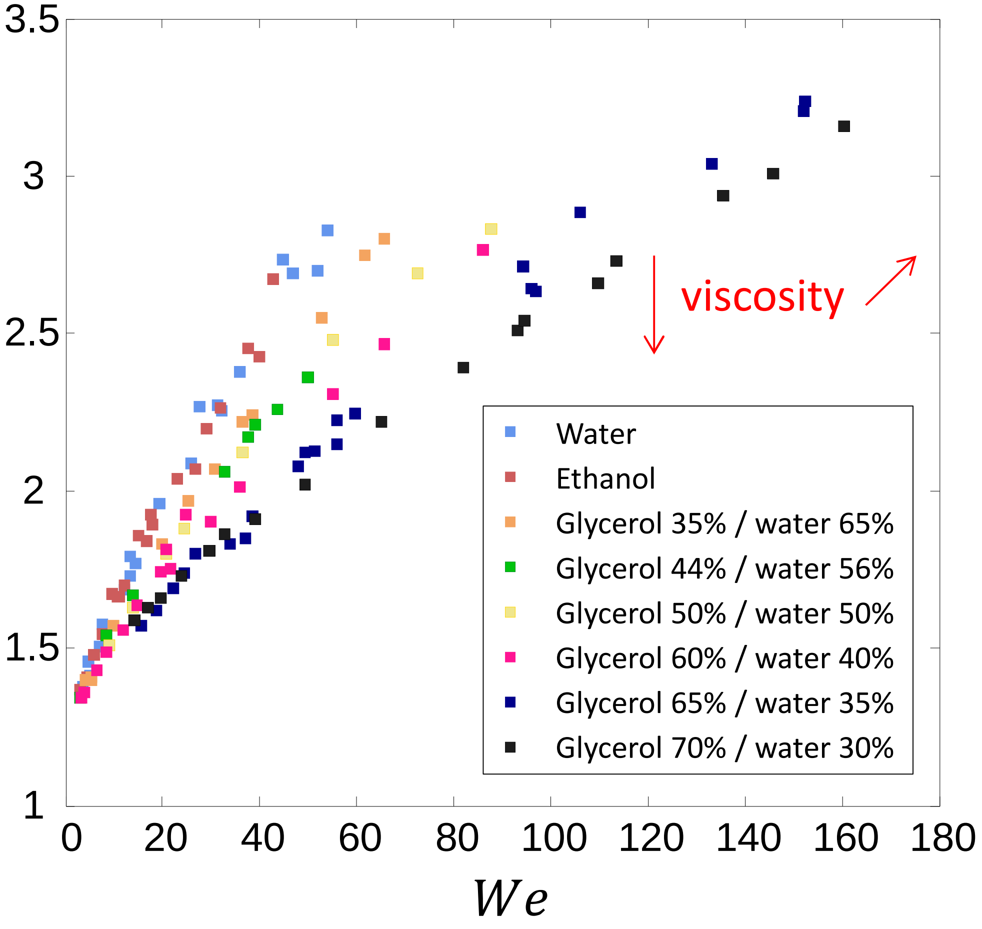


Time evolution of the horizontal spreading for drops made of 40% water and 60% glycerol by volume.

Maximum spreading diameter

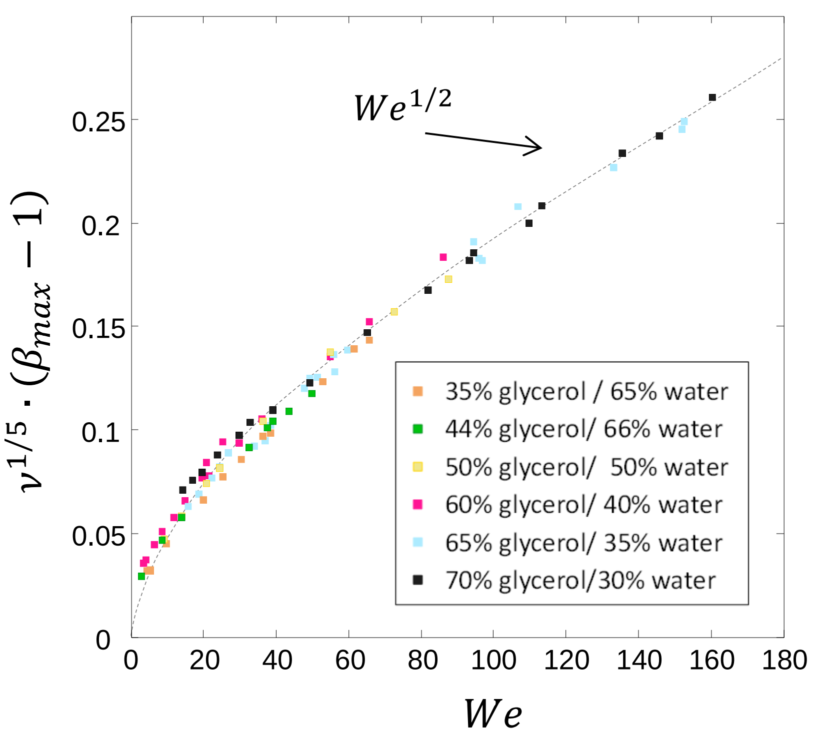
Maximum spreading factor as a function of the Weber number

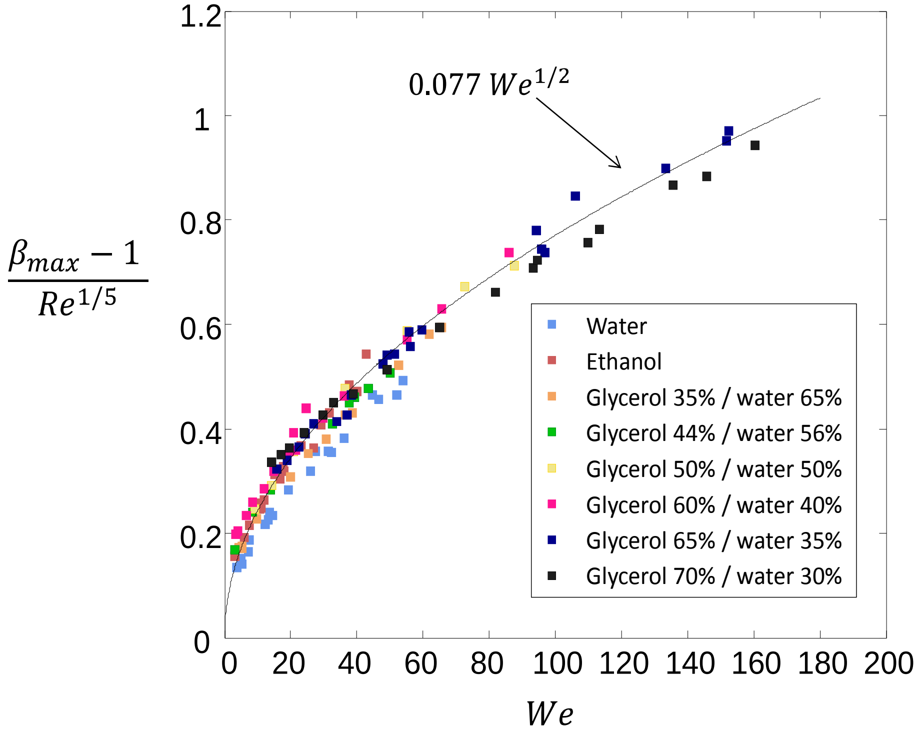
$$\beta_{max} = \frac{d_{x,max}}{d_0}$$



Maximum spreading diameter: scaling analysis

High viscosity liquids : glycerol mixtures





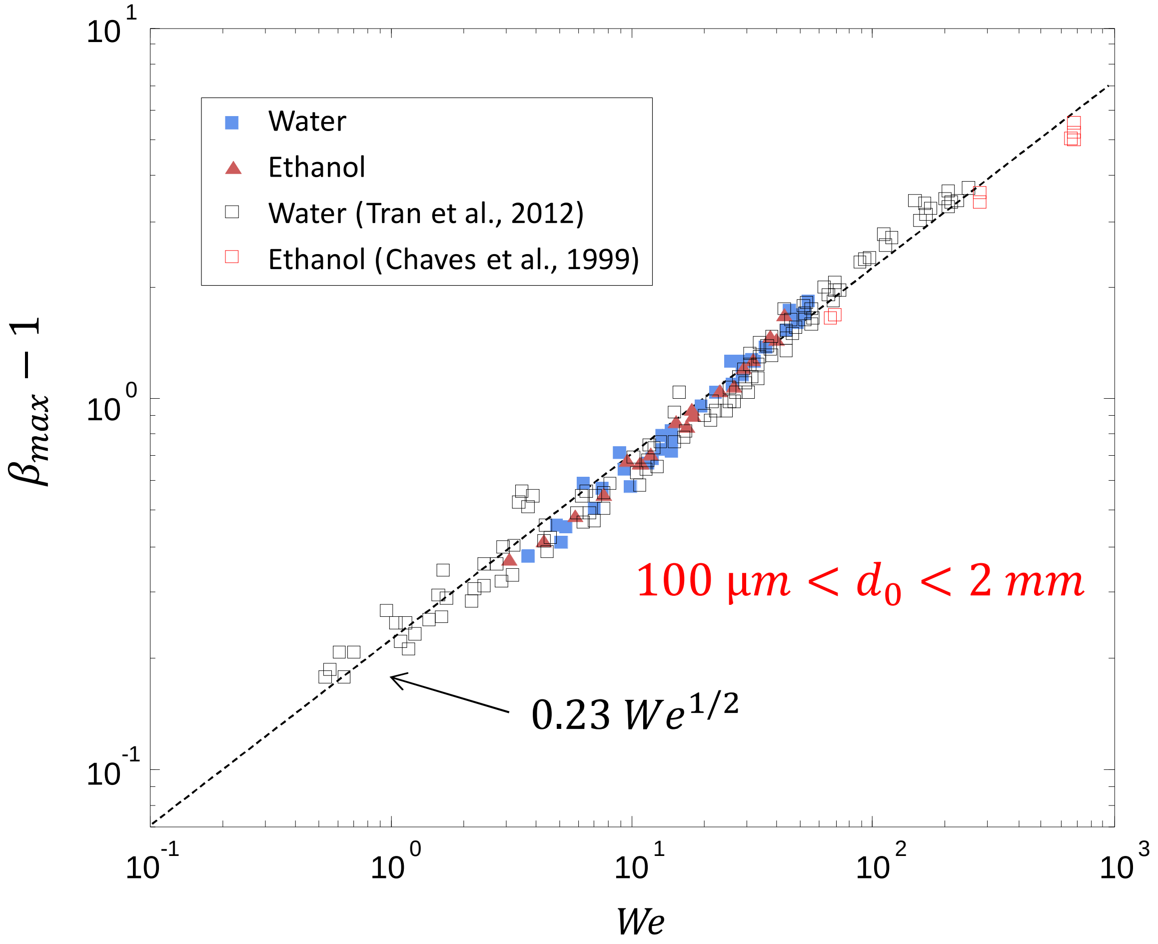
Experimental correlation : $\beta_{max} \approx 1 + 7.7 \cdot 10^{-2}\ Re^{1/5} We^{1/2}$

$\beta_{max} \sim Re^{1/5}$ (high viscosity limit for the impact on a wetting surface)

$\beta_{max} \sim We^{1/2}$ (non-dissipative limit)

Maximum spreading diameter: scaling analysis

Low viscosity liquids : Water and ethanol

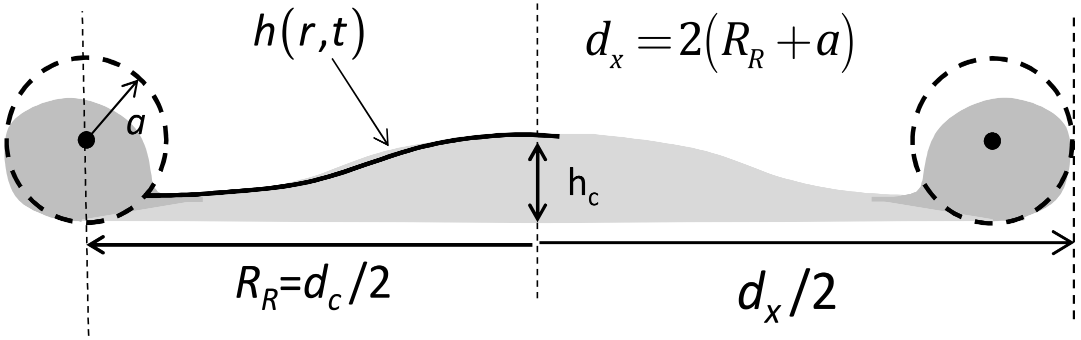


Spreading model (version 1)

Rim propagation approach initiated by Roisman et al. (2002) and Roisman et al. (2012)

Basic assumptions:

- The rim is a torus of sectional radius a.
- The remote asymptotic solution is adopted (high Re and We)



R_R: radial position of the rim
a: sectional radius of the rim
W_R: volume of the rim

Mass conservation: $W_R = (2\pi R_R)\pi a^2$

$$W_R = \frac{\pi}{6} - \int_0^{R_r} 2\pi h(r,t)\,dr = \frac{\pi}{6}\exp\left[-\frac{6\eta R_R{}^2}{(t+\tau)^2}\right]$$

drop volume

Lamella volume

Here, the parameters are made dimensionless by d_0 and u_0.

Spreading model (version 1)

Momentum conservation:

$$W_R \, \ddot{R}_R = S_{lR} \cdot \left(F_p - F_\mu - F_\sigma \right)$$

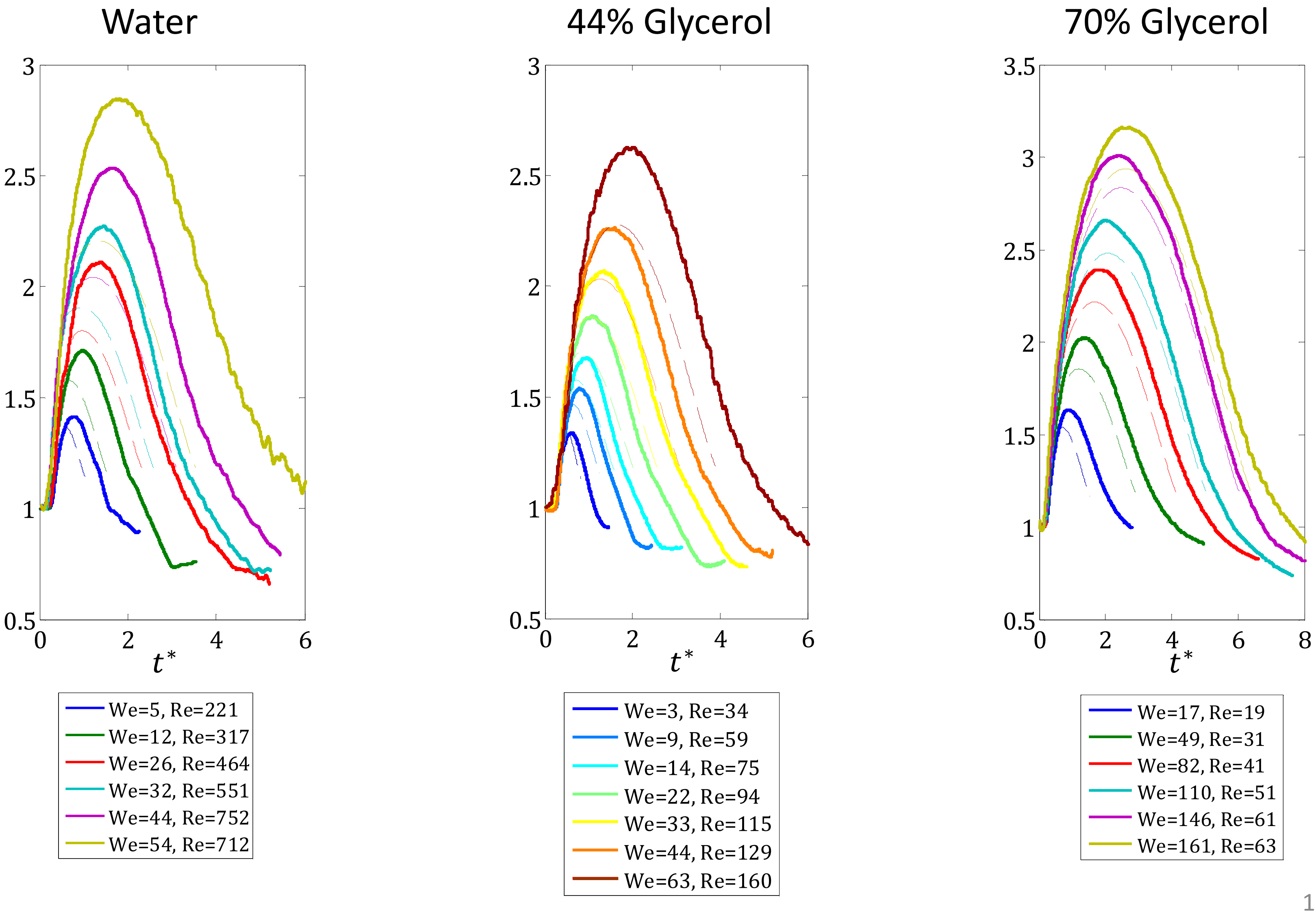
$F_p = \left(\dot{R}_R - u_{rim} \right)^2$	Momentum associated with the inflow from the lamella
$F_\sigma = \dfrac{2}{We \cdot h\left(R_R, t\right)}$	Capillary force
$F_\mu = \dfrac{6}{Re\left(t+\tau\right)}$	Viscous stress
$S_{lR} = 2\pi R_R \cdot h\left(R_R, t\right)$	Area of the interface lamella/rim
$u_{rim} = \dfrac{R_R}{t+\tau}$	Mean velocity of the liquid entering the rim

Resolution :

- Runge-Kutta (RK4)
- Initial values of R_R and $\dot{R_R}$ are adjusted so that d_x has the same value and the same rate of expansion in the simulations and in the measurements at $t = 0.5$.

Measurements vs. theoretical model (v1)

Plain lines= experiments, dot lines=model

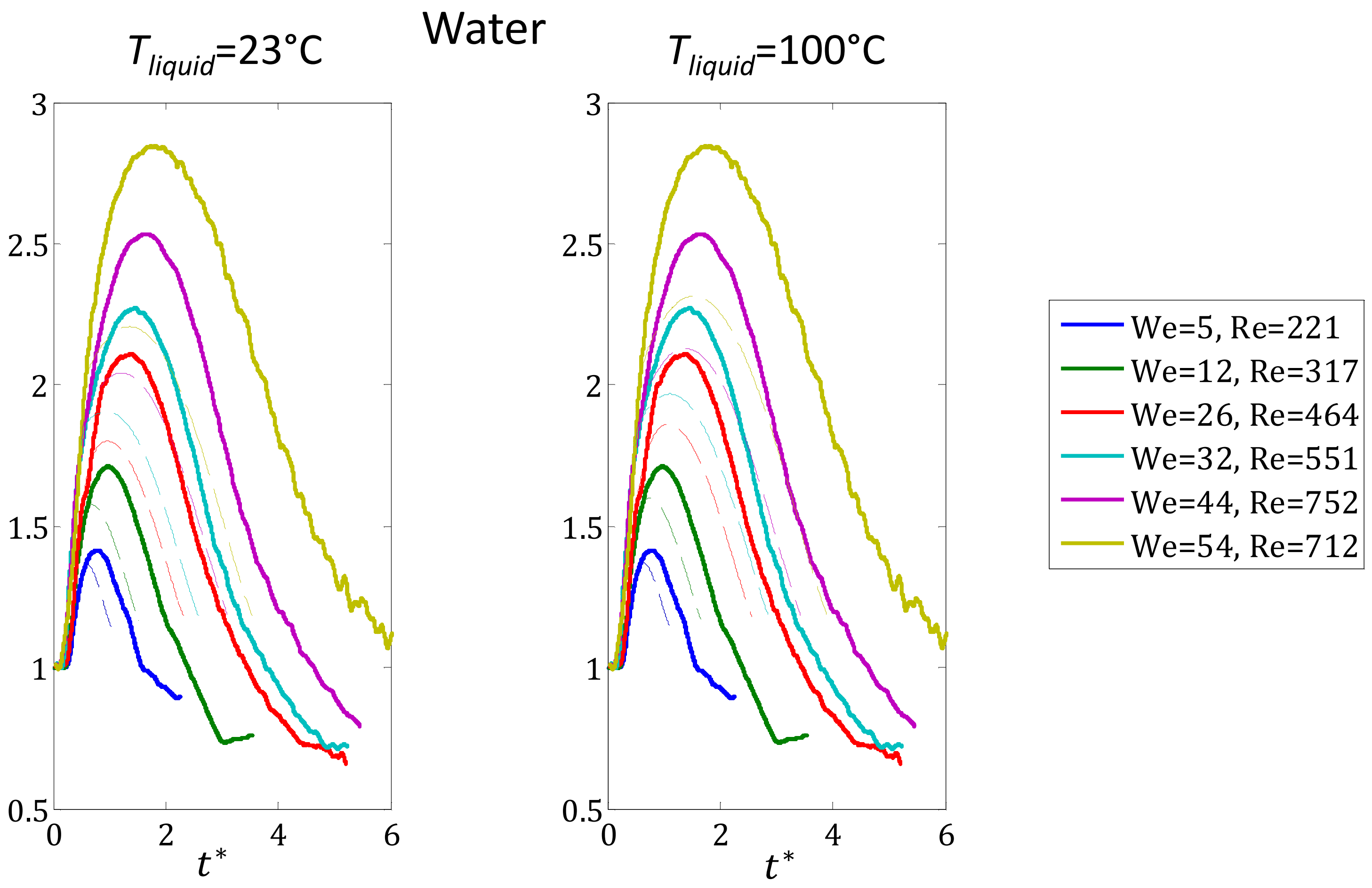

Water

44% Glycerol

70% Glycerol

Measurements vs. theoretical model (v1)

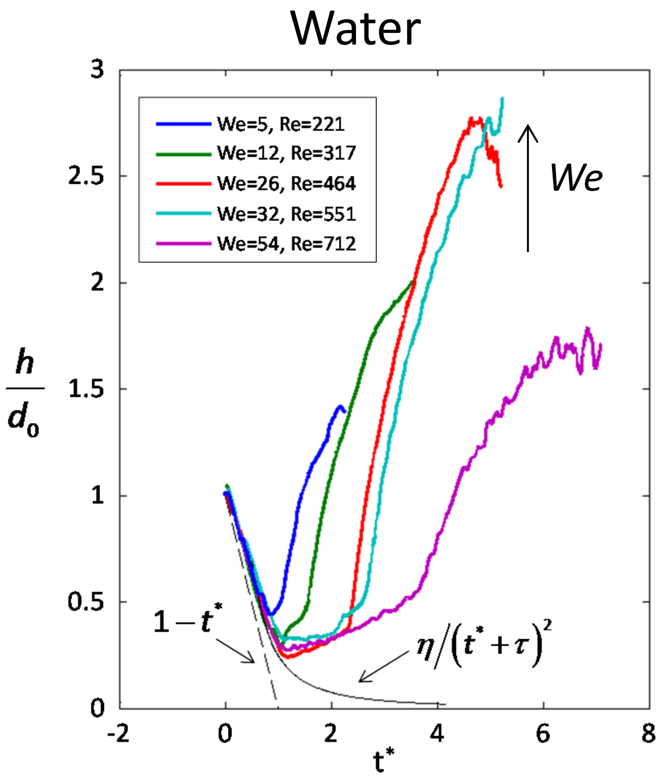
Solid lines= experiments, dot lines=model



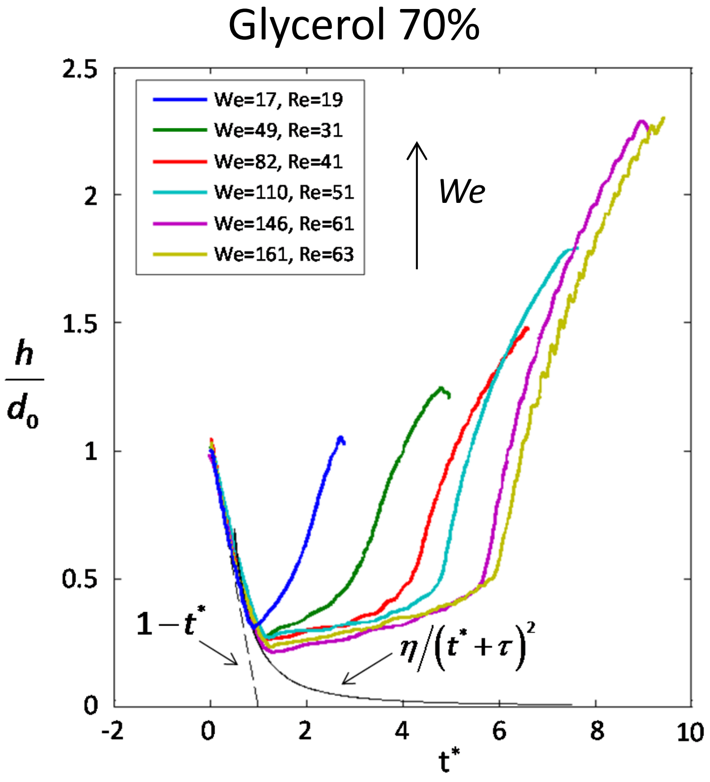
Influence of the temperature used to calculate the liquid properties (ρ, μ, σ)

Lamella thickness: comparison with experiments

Theoretical thickness: $\frac{h_c}{D_0} = \frac{\eta}{(t^* + \tau)^2}$

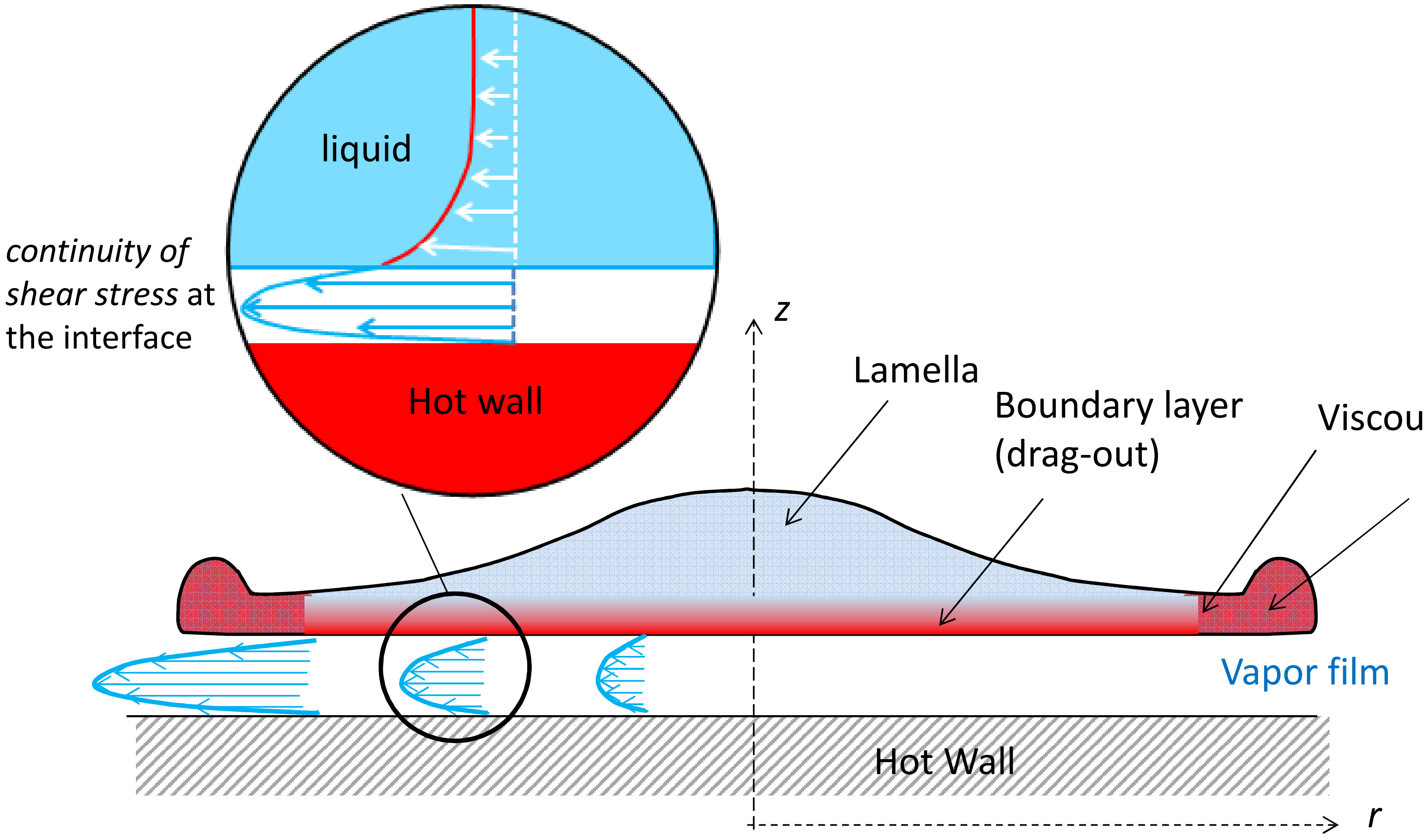


d_0= 110 µm
5 < *We* <55
Oh=0.01



d_0=250 µm
17 < *We* <170
Oh=0.21

Boundary layer entrainment



Spreading model (version 2)

Momentum conservation:

$$W_R\, \ddot{R}_R = S_{lR} \cdot \left(F_p - F_\mu - F_\sigma\right)$$

α : adjusting parameter accounting for the lack of momentum transferred to the rim

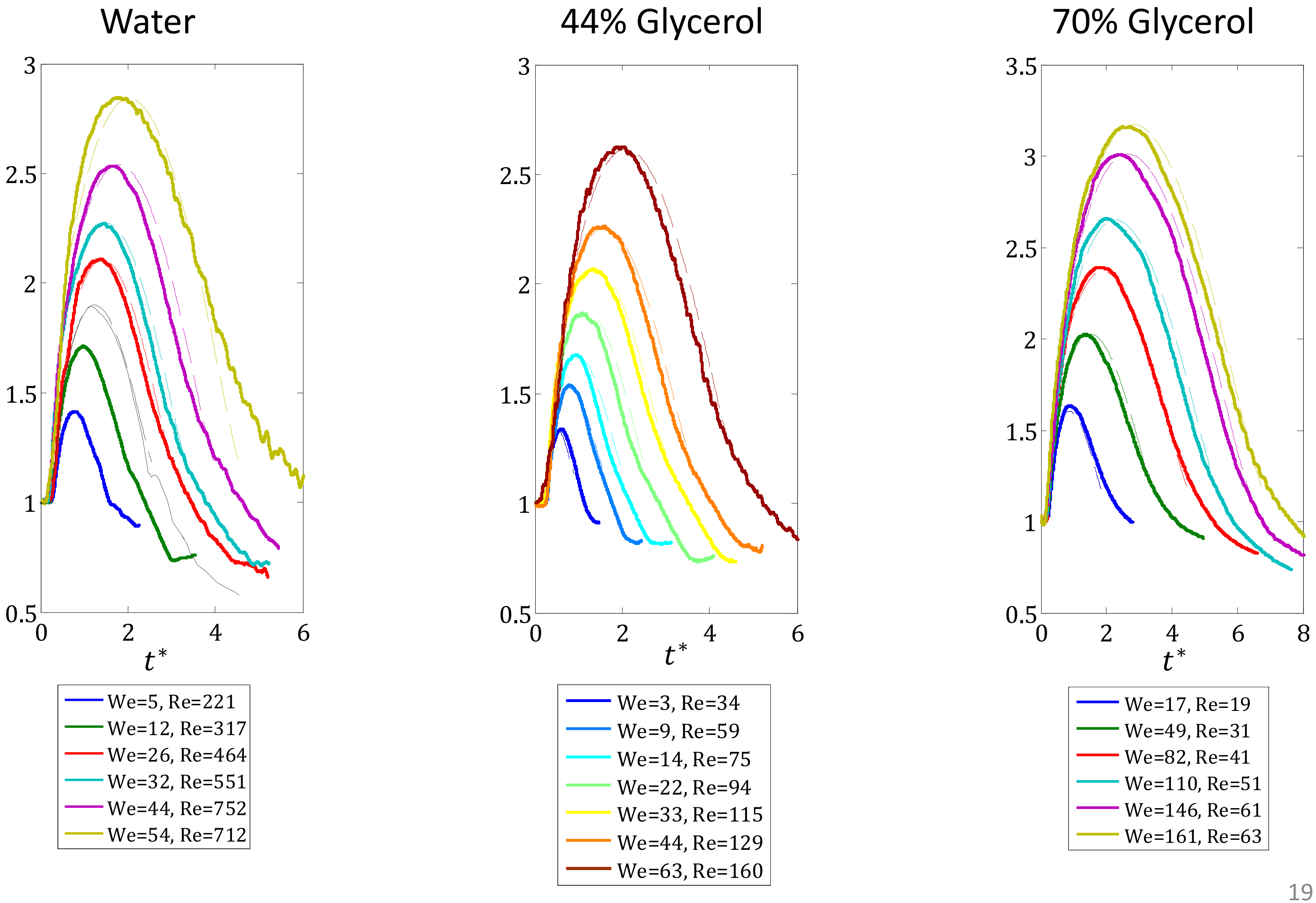
$F_p = \left(\dot{R}_R - u_{rim}\right)^2$	Momentum associated with the inflow from the lamella
$F_\sigma = \frac{2}{We \cdot h\left(R_R, t\right)}$	Capillary force
$F_\mu = \frac{6\left(1+\alpha\right)}{Re\left(t+\tau\right)}$	Viscous stress
$S_{lR} = 2\pi R_R \cdot h\left(R_R, t\right)$	Area of the interface lamella/rim
$u_{rim} = \frac{\left(1+\alpha\right)R_R}{t+\tau}$	Mean velocity of the liquid entering the rim

Mass conservation: $W_R = \left(2\pi R_R\right)\pi a^2$

$$W_R = \frac{\pi}{6} - \int_0^{R_r} 2\pi h\left(r,t\right)dr = \frac{\pi}{6}\exp\left[-\frac{6\eta R_R{}^2}{\left(t+\tau\right)^2}\right]$$

Measurements vs. theoretical model (v2)

Solid lines= experiments, dot lines=model



Water

44% Glycerol

70% Glycerol

Adjustment of the flow velocity at the entrance of the rim

$$u_{rim} = \frac{(1+\alpha)R_R}{t+\tau}$$

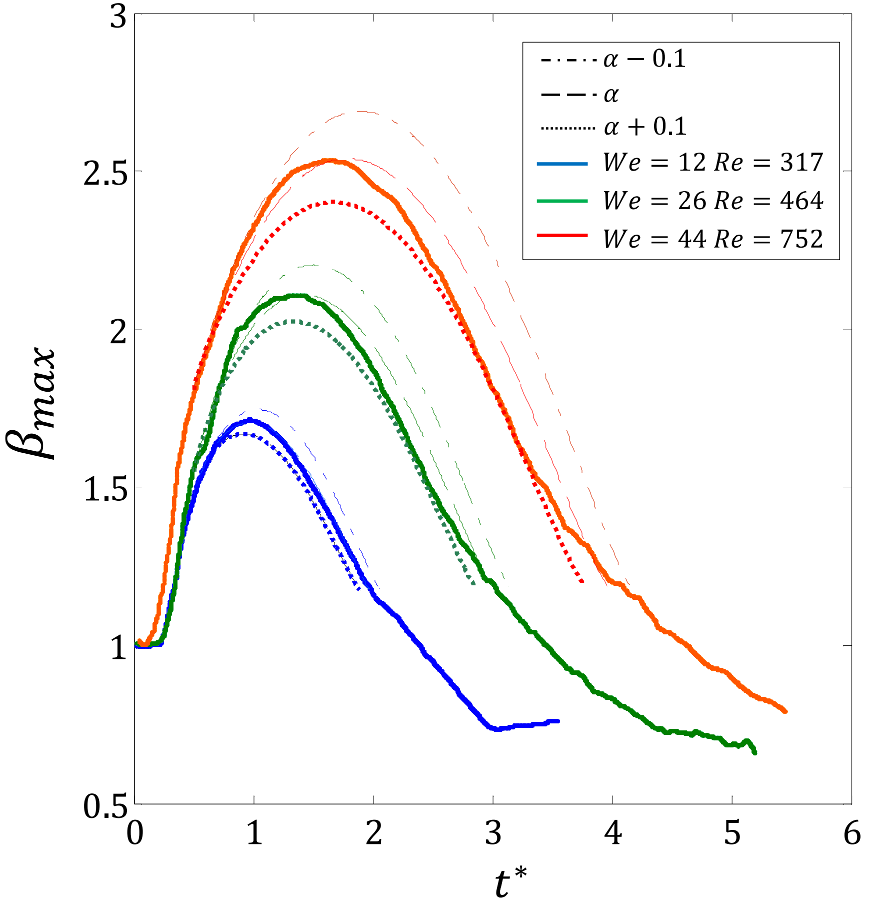
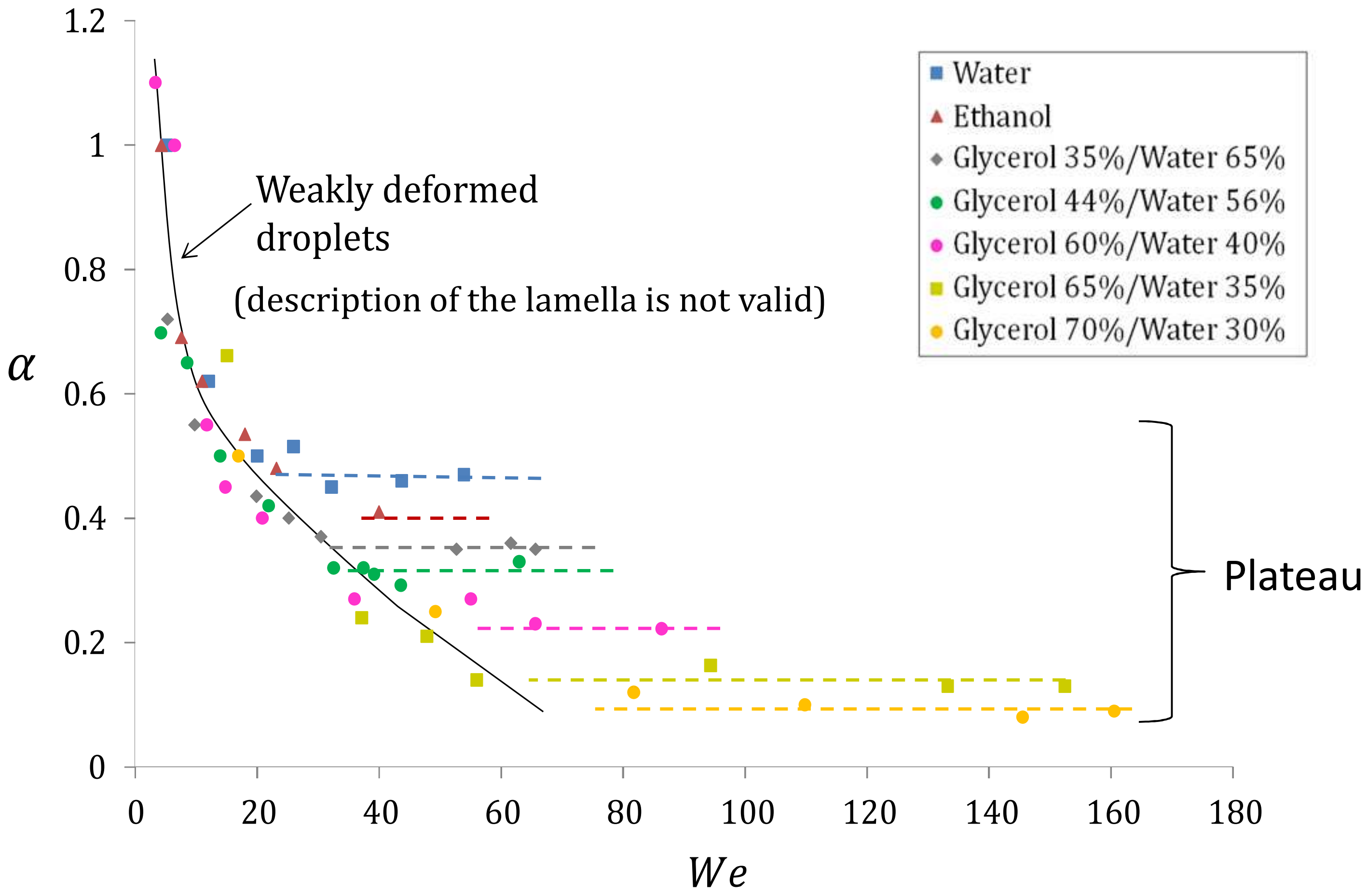


Illustration of the sensitivity to the adjustment of α.
Case of water droplets

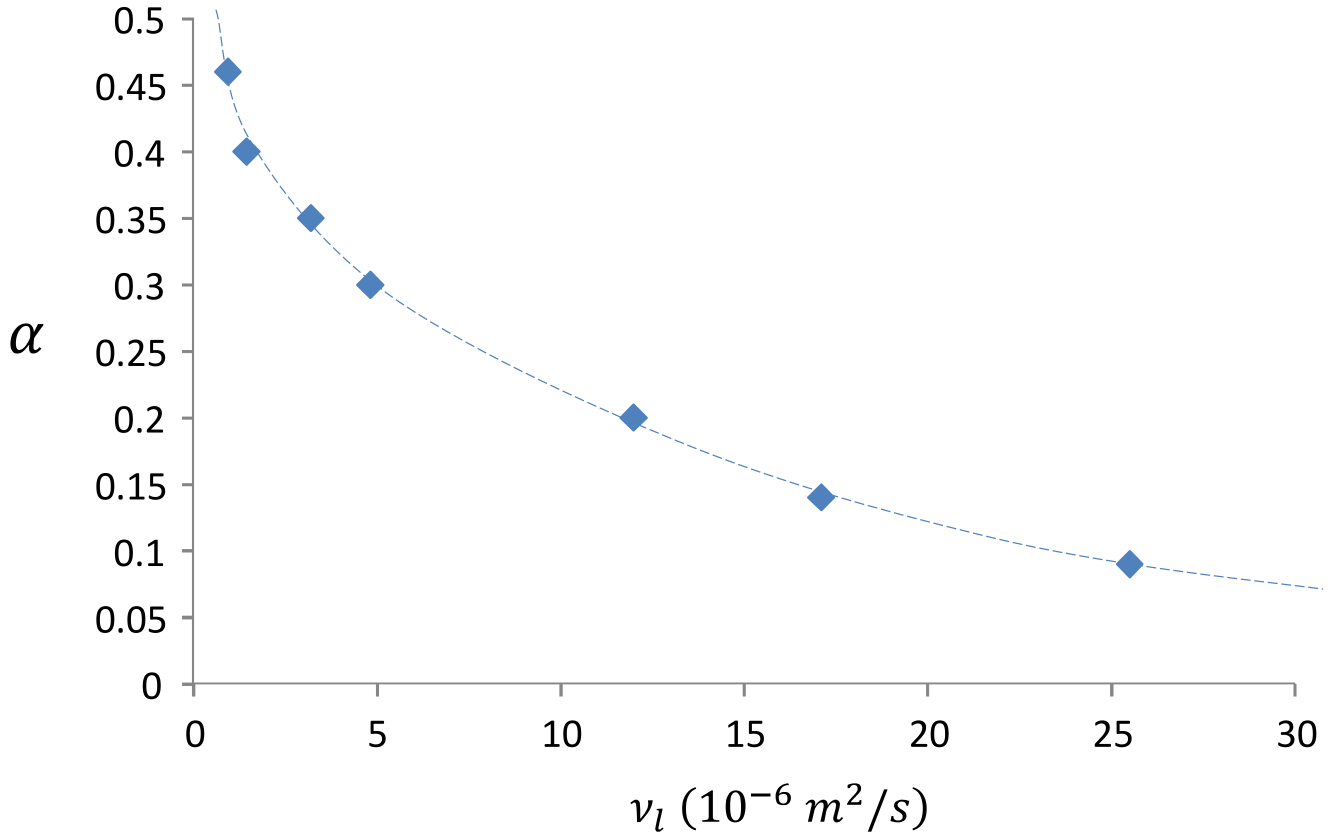
Velocity increase at the entrance of the rim



Velocity at the entrance of the rim: $u_{rim} = \dfrac{(1+\alpha)R_R}{t+\tau}$

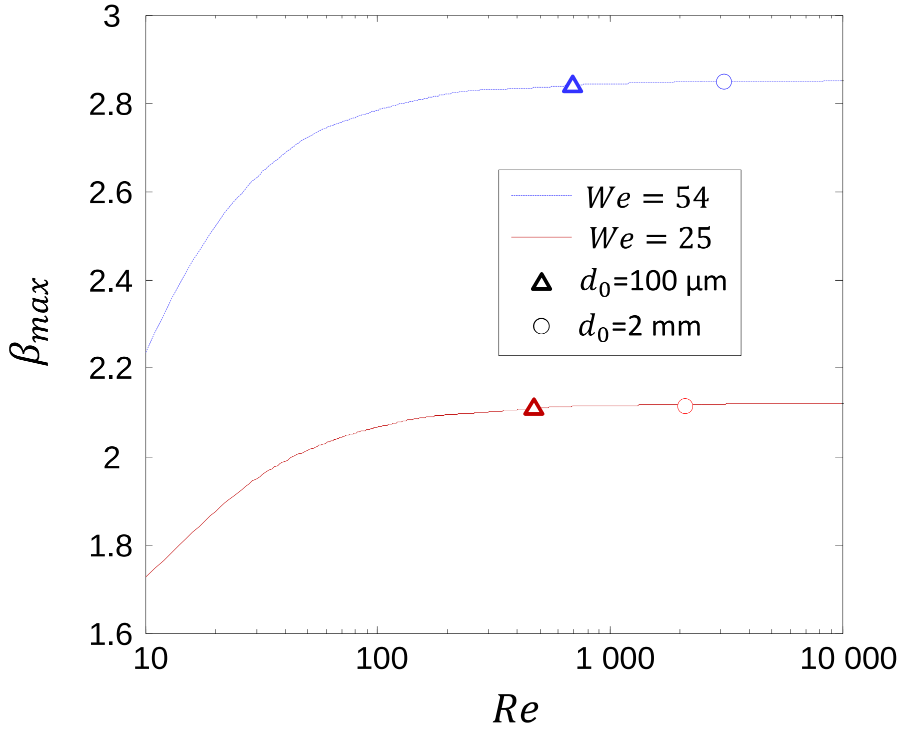
Velocity increase at the entrance of the rim

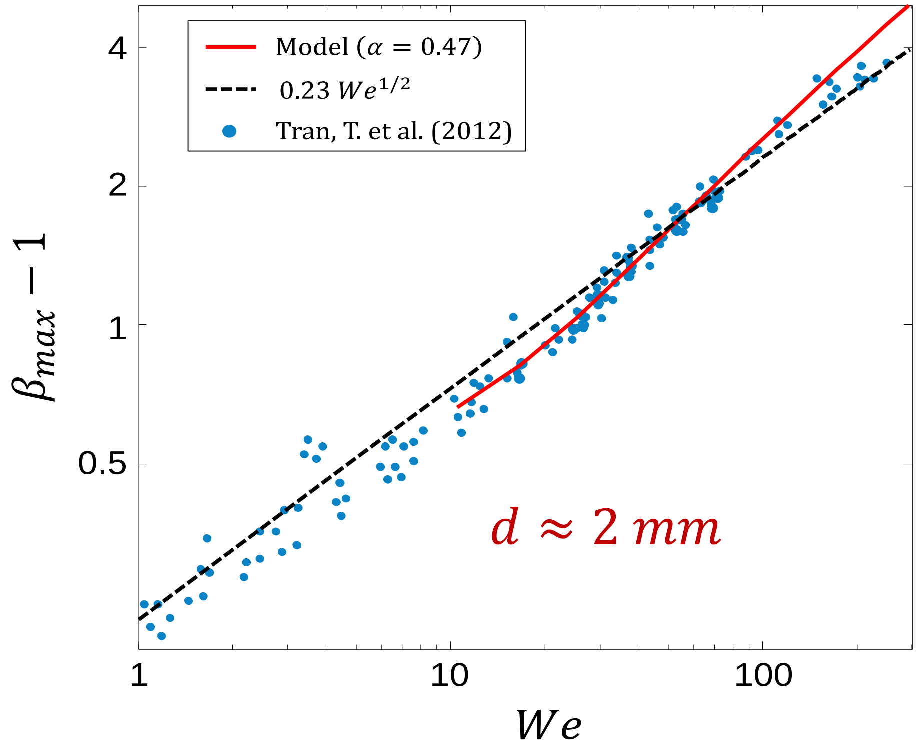
Values of α obtained at the plateau for the high We



Simulations of the spreading based on the model

Simulations of the spreading of water drops assuming $\alpha = 0.47$

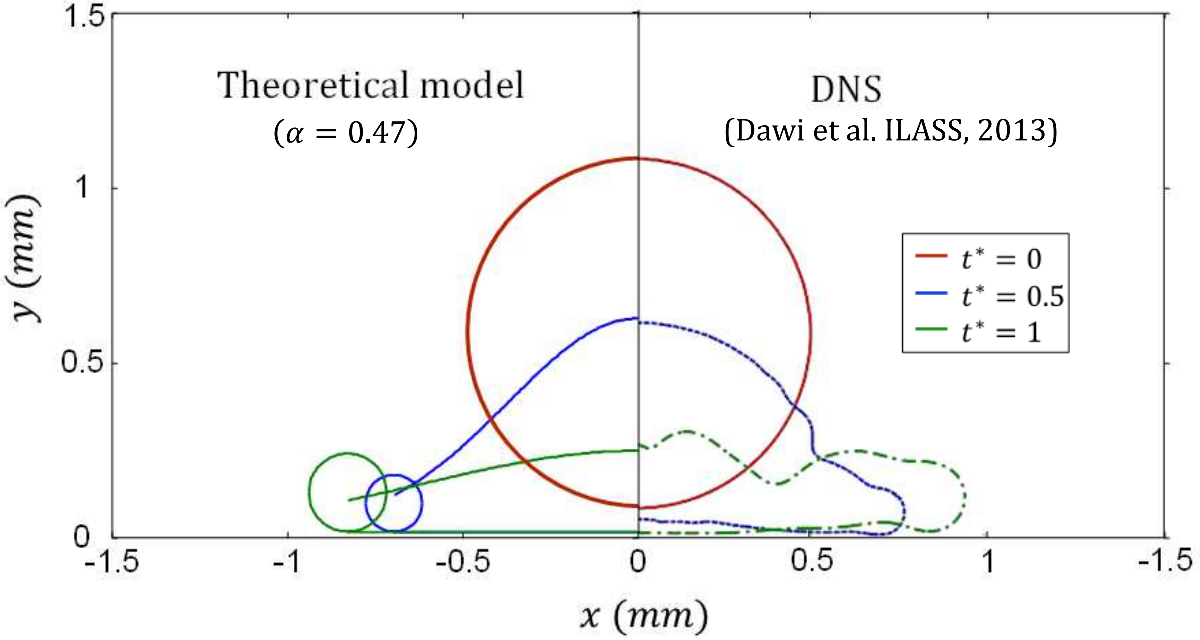




Verification of the independence of β_{max} on the droplet size

Outlooks

- Comparison to DNS



- A comprehensive model including the vapor film thickness and the vapor flow rate