Karlsruhe Institute of Technology

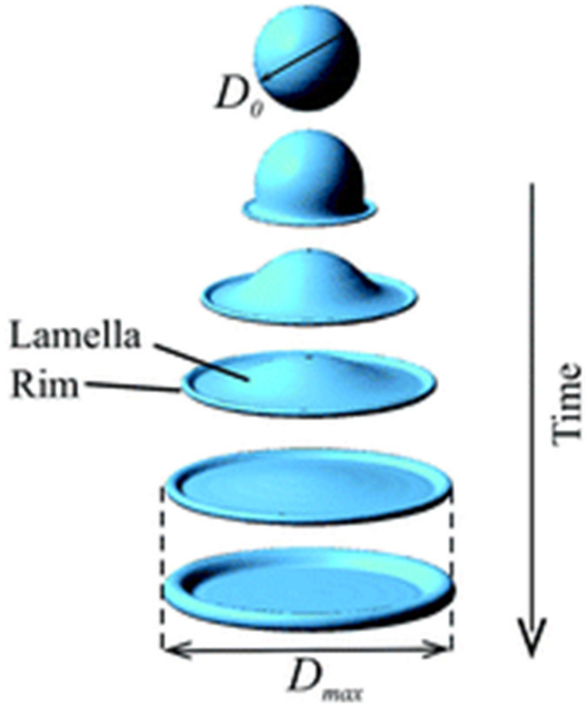
Jahrestreffen der DECHEMA-Fachgruppen
Aerosoltechnik, Gasreinigung,
Mehrphasenströmung und *Partikelmesstechnik*
28. – 30. März 2023, Paderborn

Entwicklung einer universellen analytischen Beziehung für die maximale Ausbreitung eines Tropfens beim Aufprall auf eine Wand

Development of a universal analytical relationship for the maximum spread of a drop when hitting a wall


Drop impact on a hydrophobic surface with drop rebound
(Simulation by N. Samkhaniani, KIT-ISTM)

Wörner et al., *Applied Mathematical Modeling* **95** (2021) 53-73

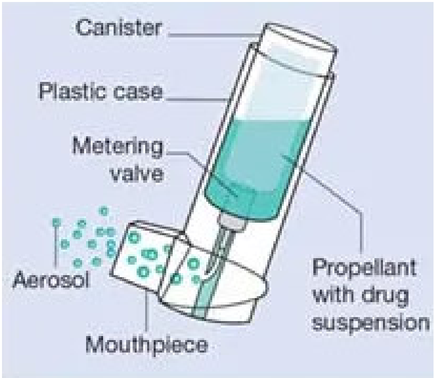


Drop impact on a hydrophilic surface
Visser et al., *Soft Matter* **11** (2015)

Agriculture
spraying of pesticides

www.spektrum.de

Medicine
aerosol drug delivery

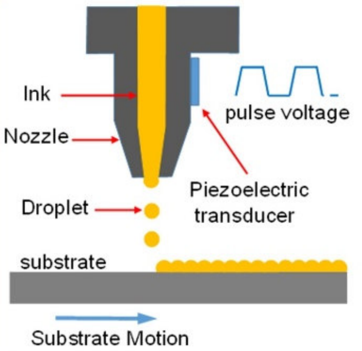


nursekey.com

Forensic
bloodstain pattern

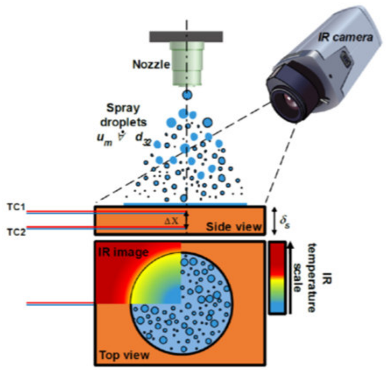
en.wikipedia.org

Manufacturing
inkjet printed solar cells



www.helmholtz-berlin.de

Heat transfer
spray cooling



Benther et al. IJHMT (2021)

Varnishing
spray painting

www.durr.com

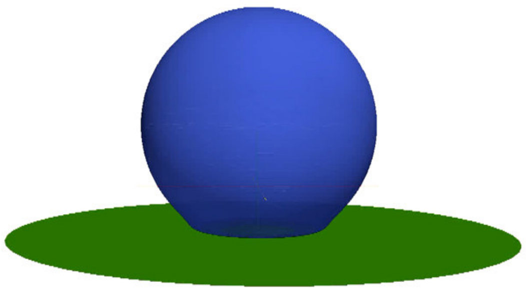
CRC/Transregio 150
Turbulent, chemically reactive multi-phase flows near walls

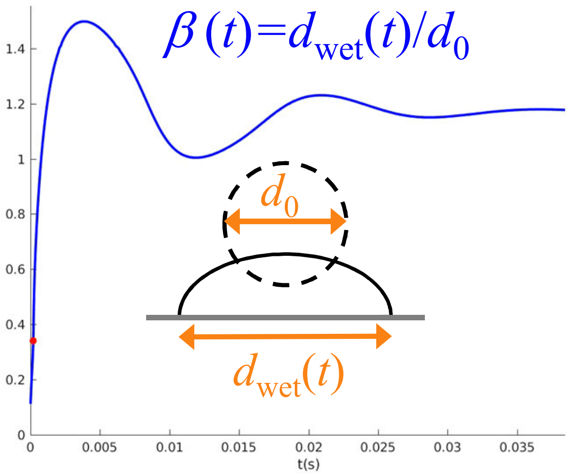
Internal combustion engine
Fuel spray

Exhaust pipe
AdBlue spray

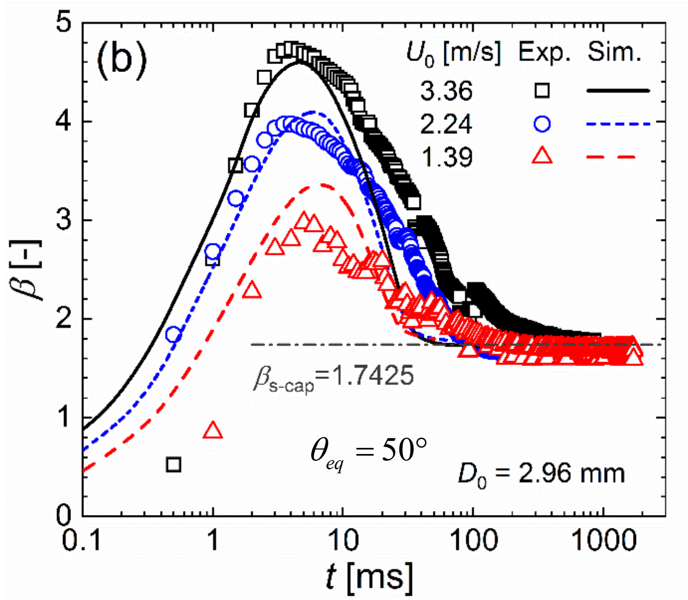
Motivation

- Predicting the interaction of a single drop with a dry horizontal surface

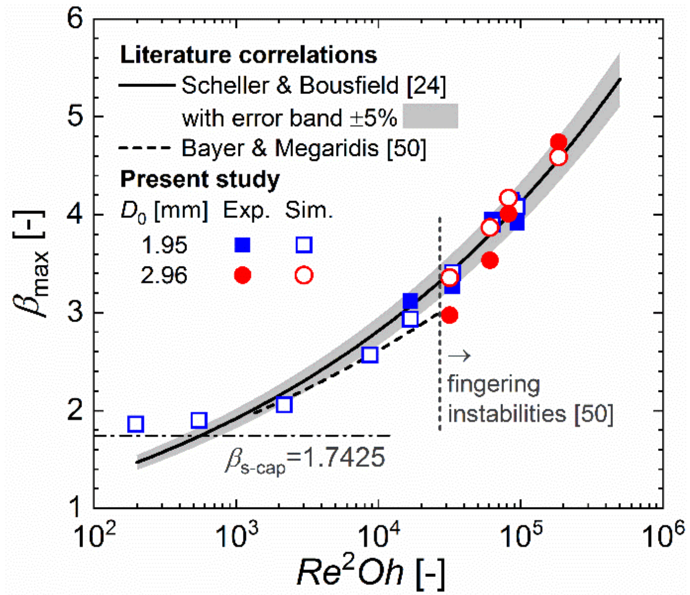




Spreading factor $\beta(t)$



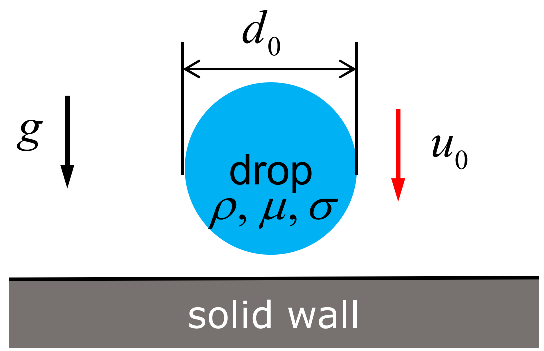
Max. spread factor β_m

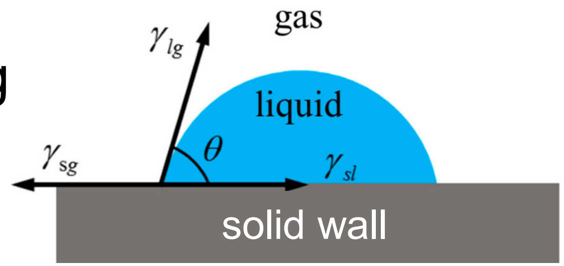


📖 M. Börnhorst, X. Cai, M. Wörner, O. Deutschmann, Maximum spreading of urea water solution during drop impingement, *Chem. Eng. Technol.* **42** (2019) 2419-2427

Objective

- Maximum spread diameter depends on physical properties, on drop size/velocity and on wettability of the solid surface
  - Weber number $We = \rho d_0 u_0^2/\sigma$
  - Reynolds number $Re = \rho d_0 u_0/\mu$ (or $Oh = \sqrt{We}/Re$)
  - Contact angle θ (static, equilibrium, advancing, receding, dynamic)
- Classification of theoretical models for maximum spreading
  - Models based on scaling relations valid in certain regimes
  - Mechanistic models based on momentum or **energy balance**
- A universal mechanistic model based on the energy balance is missing
  - Difficulty with low/high viscosity liquids and hydrophilic/hydrophobic surfaces
  - Here, significant progress in development of a <u>universal energy balance model</u> is reported





Outline

- Introduction
  - Motivation and objective
- **Literature survey on models for maximum spreading**
  - Energy balance (EB) approach
  - Scaling in different regimes
- New concepts for closure terms in the energy balance
  - Gas-liquid surface area
  - Dissipation upon maximum spread
- Closure of dissipation function and test of the novel model
  - Parameter determination by asymptotic analysis and experiments
  - Test against experimental data sets from literature
- Conclusions and outlook

Balance of mechanical energy

- General energy balance between initial state ($t = 0$) and state at time $t > 0$
  - Consideration of liquid kinetic energy (E_k) and surface energy (E_s)
  - Gravitational energy (E_g) can be neglected because E_g/E_s is typically small
  - Energy lost by (viscous) dissipation $W \geq 0$
  - Normalization of EB by σS_0, where S_0 denotes the initial gas-liquid surface area

$$\frac{E_{k,0} - E_k(t)}{\sigma S_0} + \frac{E_{s,0} - E_s(t)}{\sigma S_0} = \frac{W(t)}{\sigma S_0} \qquad \frac{E_{k,0}}{\sigma S_0} = \frac{(\frac{1}{2}\rho u_0^2)(\frac{\pi}{6} d_0^3)}{\sigma \pi d_0^2} = \frac{\frac{\pi}{12}\rho u_0^2 d_0^3}{\sigma \pi d_0^2} = \frac{We}{12}$$

- Energy balance at time of maximum spreading ($t = t_m$) assuming $E_k(t_m) = 0$

$$\frac{We}{12} + 1 - \underbrace{\frac{S(t_m)}{S_0}}_{=s_m} + \frac{\cos\theta}{4}\beta_m^2 = \underbrace{\frac{W(t_m)}{\sigma S_0}}_{=w_m}$$

To obtain a relation for β_m models for s_m and w_m are required
$\rightarrow$ see slides 11 and 12

Scaling in capillary regime – $\beta_m \sim We^{1/2}$

- Initial kinetic energy is completely converted in surface energy at max. spread

$$\frac{E_{k,0}}{\sigma S_0} = \frac{We}{12} \sim \frac{E_{s,m}}{\sigma S_0}$$

- Estimation of surface energy
  - Change of Gibbs free interfacial energy (per unit area)
  - At maximum spread

Young's equation

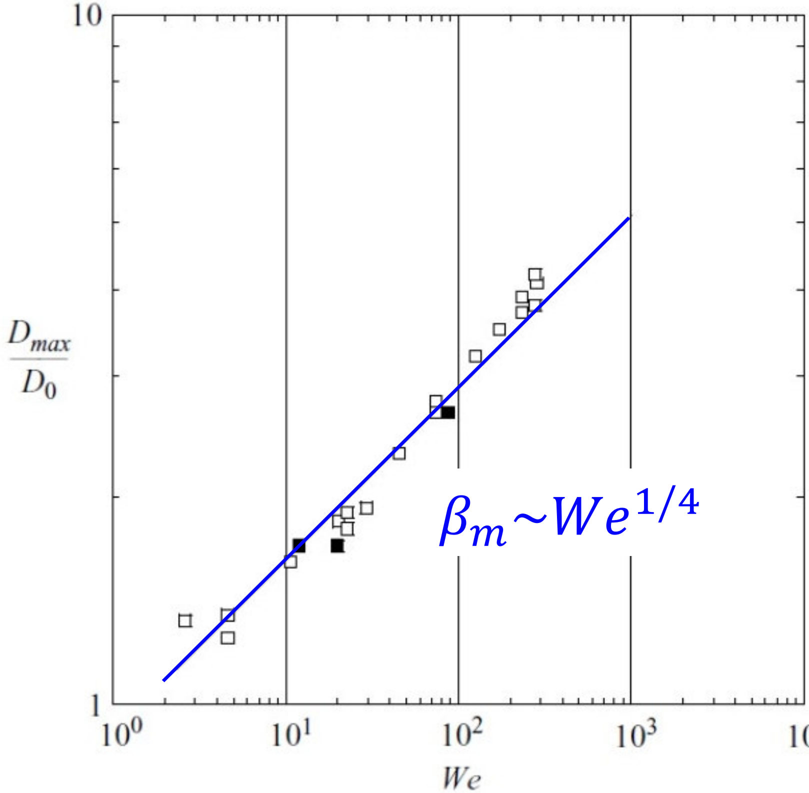
$$\Delta G = \underbrace{\gamma_{gl}}_{=\sigma} + \underbrace{\gamma_{sl} - \gamma_{sg}}_{-\sigma\cos\theta} = \sigma(1-\cos\theta)$$

$$\frac{E_{s,m}}{\sigma S_0} \sim \frac{\Delta G \cdot A_{\text{wet}}}{\sigma S_0} = \frac{\sigma(1-\cos\theta)\frac{\pi}{4}d_m^2}{\pi\sigma d_0^2} = \frac{1-\cos\theta}{4}\beta_m^2 \quad \rightarrow \quad \beta_m \sim \sqrt{\frac{3We}{1-\cos\theta}} \sim We^{1/2}$$

📖 R.E. Ford, C.G.L. Furmidge, Impact and spreading of spray drops on foliar surfaces, Society of Chemical Industry, London, 1967, 417-432
📖 E.W. Collings, A.J. Markworth, J.K. McCoy, J.H. Saunders, *J. Mater. Sci.* **25** (1990) 3677-3682
📖 T. Bennett, D. Poulikakos, *J. Mater. Sci.* **28** (1993) 963-970

Scaling in capillary regime – $\beta_m \sim We^{1/4}$

- Experiments of Clanet et al. (2004)
  - Impact of water droplets on smooth superhydrophobic surface ($\theta_{eq} = 170°$)
  - Observed experimental scaling $\beta_m \sim We^{1/4}$
  - Explanation by “effective gravity” force due to drop deceleration after impact
- Exp. by Attane et al. (2007), Laan et al. (2014)
  - Scaling $\beta_m \sim We^{1/4}$ is consistent for water but does not hold for other liquids (e.g. blood)
  - The exact conditions under which this scaling occurs are still unclear



C. Clanet, C. Beguin, D. Richard, D. Quere, Maximal deformation of an impacting drop, *J. Fluid Mech.* **517** (2004) 199-208
P. Attane, F. Girard, V. Morin, An energy balance approach of the dynamics of drop impact on a solid surface, *Phys. Fluids* **19** (2007) 012101
N. Laan, K.G. de Bruin, D. Bartolo, C. Josserand, D. Bonn, *Physical Review Applied* **2** (2014) 044018

Scaling in viscous regime

- Initial kinetic energy is mainly dissipated at maximum spread

$$\frac{E_{k,0}}{\sigma S_0} = \frac{We}{12} \sim \frac{W_m}{\sigma S_0} \qquad W_m = \int_0^{t_m} \int_{V_{\mathrm{drop}}} \mu\left(\nabla \mathbf{u} + (\nabla \mathbf{u})^{\mathrm{T}}\right) : \nabla \mathbf{u}\, \mathrm{d}V \mathrm{d}t$$

- Chandra & Avedisian (1991)

$$W_m \sim \mu \frac{u_0^2}{h_m^2} \cdot d_0^3 \cdot \frac{d_0}{u_0} \sim \frac{\mu u_0 d_0^4}{h_m^2} \qquad h_m d_m^2 \sim d_0^3 \quad \rightarrow \quad \beta_m \sim Re^{1/4}$$

volume conservation
(h_m = drop height at maximum spread)

- Clanet et al. (2004)

$$W_m \sim \mu \frac{u_0^2}{h_m^2} \cdot d_m d_0^2 \cdot \frac{d_0}{u_0} \sim \frac{\mu u_0 d_m d_0^3}{h_m^2} \quad \rightarrow \quad \beta_m \sim Re^{1/5}$$

(Scaling observed in experiment of Madejski)

📖 S. Chandra, C.T. Avedisian, *Proc. Royal Society London. Series A: Mathematical and Physical Sciences* **432** (1991) 13-41
📖 C. Clanet, C. Beguin, D. Richard, D. Quere, Maximal deformation of an impacting drop, *J. Fluid Mech.* **517** (2004) 199-208
📖 J. Madejski, Solidification of droplets on a cold surface, *Int. J. Heat Mass Transf.* **19** (1976) 1009-1013

Transition between both regimes

- Capillary regime $P < 1$
  - All initial energy is transferred in surface energy at maximum spreading

$$\beta_m \sim We^{1/2}$$

- Viscous regime $P > 1$
  - Clanet et al. (2004), Fedorchenko et al. (2005), Roisman (2009)

$$\beta_m \sim Re^{1/5}$$

- Impact parameter P serves to distinguish both regimes
  - $b = 4/5$ (Clanet), $b = 1/2$ (Fedorchenko), $b = 2/5$ (Eggers)

$$P = \frac{We}{Re^b}$$

- Rescaling methods (e.g. Laan et al., 2014)
  - Regime discrimination parameter $A = 1.24$ is of order 1

$$\beta_m Re^{-1/5} = \frac{P^{1/2}}{A + P^{1/2}}$$

📖 C. Clanet, C. Beguin, D. Richard, D. Quere, Maximal deformation of an impacting drop, *J. Fluid Mech.* **517** (2004) 199-208
📖 A.I. Fedorchenko, A.-B. Wang, Y.-H. Wang, *Phys. Fluids* **17** (2005) 093104
📖 I.V. Roisman, Inertia dominated drop collisions, Part II., *Phys. Fluids* **21** (2009)
📖 J. Eggers, M.A. Fontelos, C. Josserand, S. Zaleski, *Phys. Fluids* **22** (2010) 062101
📖 N. Laan, K.G. de Bruin, D. Bartolo, C. Josserand, D. Bonn, *Physical Review Applied* **2** (2014) 044018

EB – Modeling of gas-liquid surface area s_m

- Geometrical approximations for drop shape
  - Disk with negligible height

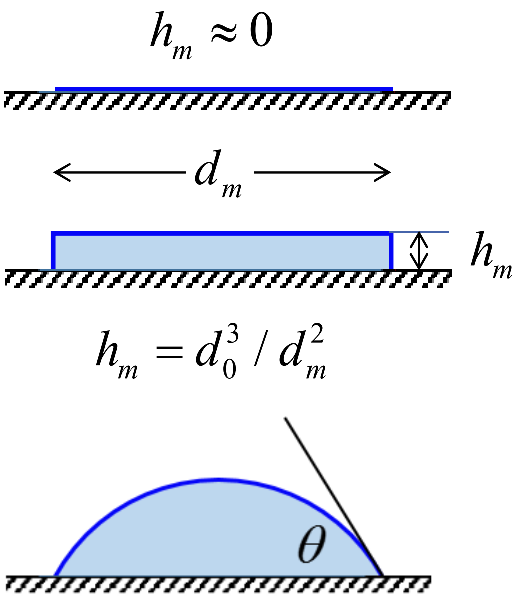
$$s_{\text{disk}}(\beta) = \frac{\beta^2}{4}$$

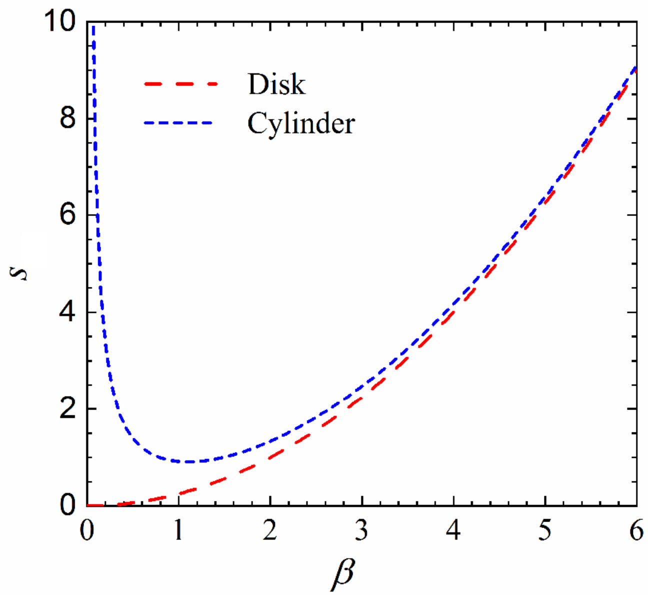
  - Cylinder with finite height

$$s_{\text{cyl}}(\beta) = \frac{\beta^2}{4} + \frac{2}{3\beta}$$

  - Spherical cap (sc)

$$s_{\text{sc}}(\theta) = \sqrt[3]{\frac{2}{(2+\cos\theta)^2(1-\cos\theta)}}$$





📖 R.E. Ford, C.G.L. Furmidge, Impact and spreading of spray drops on foliar surfaces, Society of Chemical Industry, London, 1967, 417-432
📖 T. Mao, D.C.S. Kuhn, H. Tran, Spread and rebound of liquid droplets upon impact on flat surfaces, *AIChE J.* **43** (1997) 2169-2179
📖 H. Park, W.W. Carr, J. Zhu, J.F. Morris, Single drop impaction on a solid surface, *AIChE J.* **49** (2003) 2461-2471

EB – Modeling of dissipation w_m

- Mechanistic dissipation models

$$W_m = \int_0^{t_m} \int_{V_{\text{diss}}} \mu \left(\nabla \mathbf{u} + (\nabla \mathbf{u})^{\mathrm{T}} \right) : \nabla \mathbf{u} \, \mathrm{d}V \mathrm{d}t$$

$$\approx \mu \cdot u_c^2 \cdot L_c^{-2} \cdot t_m \cdot V_{\text{diss}}$$

  - Various proposals for u_c, L_c, t_m all yield $w_m = W_m/(\sigma S_0) \sim \beta_m^n$ with exponent $n = 2 - 6.5$
- Combinations of models for s_m and w_m give energy balance models of very different form
- *Is dissipation model appropriate? Different dissipation contributions: viscous b.l., c.l. friction, ...*

Literature	Energy models
Chandra and Avedisian (1991)[21]	$1.5\frac{\mathrm{We}}{\mathrm{Re}}\beta_{max}^4 + (1-\cos\theta)\beta_{max}^2 - \left(\frac{1}{3}\mathrm{We}+4\right) \approx 0$
Pasandideh-Fard *et al.* (1996)[22]	$\beta_{max} = \sqrt{\frac{\mathrm{We}+12}{3(1-\cos\theta)+4\frac{\mathrm{We}}{\sqrt{\mathrm{Re}}}}}$
Mao *et al.* (1997)[35]	$\left[\frac{1}{4}(1-\cos\theta)+0.2\frac{\mathrm{We}^{0.83}}{\mathrm{Re}^{0.33}}\right]\beta_{max}^3 - \left(\frac{\mathrm{We}}{12}+1\right)\beta_{max} + \frac{2}{3}$
Ukiwe and Kwok (2005)[23]	$(\mathrm{We}+12)\beta_{max} = 8 + \beta_{max}^3\left[3(1-\cos\theta)+4\frac{\mathrm{We}}{\sqrt{\mathrm{Re}}}\right]$
Gao and Li (2014)[34]	$1+\frac{\mathrm{We}}{12} = \frac{1}{6}\left(\frac{D}{r_c}+\frac{D}{R_c}\right) + 4\theta_a\frac{r_c R_c}{D^2} + \left(\frac{R_c}{D}-\frac{r_c}{D}\sin\theta_a\right) + \left(\frac{R_c}{D}+\frac{r_c}{D}\sin\theta_a\right)^2\left(\frac{4}{3}\frac{\mathrm{We}}{\sqrt{\mathrm{Re}}}-\cos\theta_a\right)$
Wildeman *et al.* (2016)[9]	$\frac{12}{\mathrm{We}}+\frac{1}{2} = \beta_{max}^2\frac{3(1-\cos\theta)}{\mathrm{We}} + \frac{\alpha}{\sqrt{\mathrm{Re}}}\beta_{max}^2\sqrt{\beta_{max}-1}$ no-slip, $\mathrm{We} > 30$

Table from Aksoy et al., *Phys. Fluids* **34** (2022) 042106

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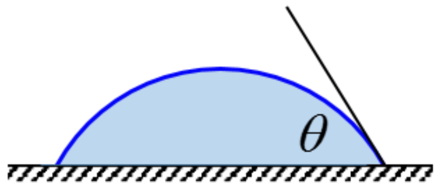
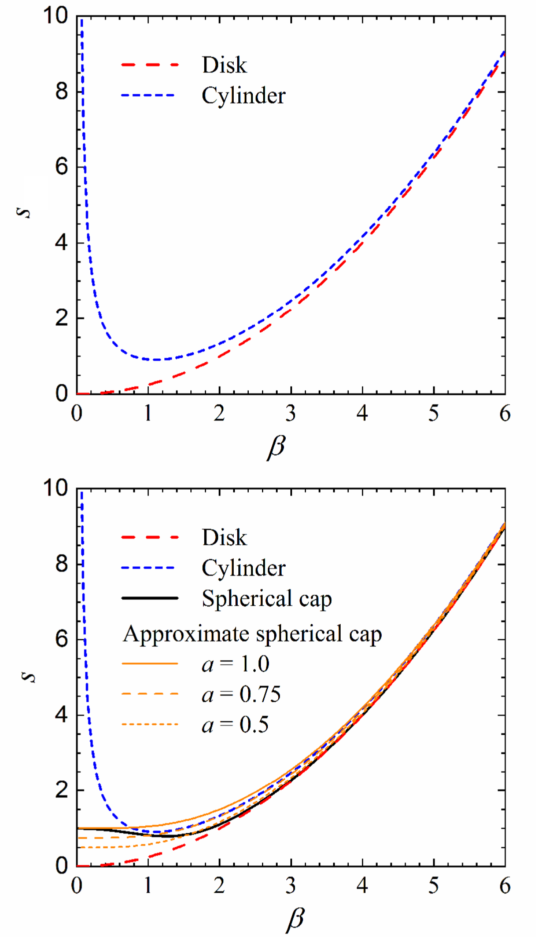
New model for gas-liquid surface area

- The disk and cylinder shape models are not suitable for low β (hydrophobic surfaces) and cannot describe the initial state where $s_0 = 1$
- Spherical cap $s_{sc} = s_{sc}(\theta)$
  - New relation $s_{sc} = s_{sc}(\beta)$



$$s_{sc}(\beta) = \frac{\sqrt[3]{\beta^6 + 8\sqrt{\beta^6 + 16} + 32}}{4} - \frac{\beta^2}{4} + \frac{\beta^4}{4\sqrt[3]{\beta^6 + 8\sqrt{\beta^6 + 16} + 32}}$$



- Approximate spherical cap (new model)

$$\beta^6 + 8\sqrt{\beta^6 + 16} + 32 \approx (\beta^2 + 4a)^3 \quad \rightarrow \quad s_{asc}(\beta, a) = a + \frac{1}{4}\frac{\beta^4}{\beta^2 + 4a}$$

New concept for modeling of dissipation

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- Existing models do not respect the upper physical bound for dissipation
- Energy balance between initial state and terminal deposition state ($t = t_{eq}$)

$$\frac{We}{12} + 1 - \underbrace{\frac{S(t_{eq})}{S_0}}_{=s_{eq}} + \frac{\cos\theta}{4}\beta_{eq}^2 = \underbrace{\frac{W(t_{eq})}{\sigma S_0}}_{=w_{eq}} \xrightarrow{eq = sc} w_{eq} = \frac{We}{12} + \underbrace{1 - \sqrt[3]{(2+\cos\theta)(1-\cos\theta)^2/4}}_{0 \le w_{eq,s} \le 1}$$

$$s_{eq} = s_{sc}(\theta) = \sqrt[3]{\frac{2}{(2+\cos\theta)^2(1-\cos\theta)}} \qquad \beta_{eq} = \beta_{sc}(\theta) = \sqrt[3]{\frac{4\sin^3\theta}{(2+\cos\theta)(1-\cos\theta)^2}}$$

- New model for dissipation upon maximum spread

$$\boxed{w_m = f_w w_{eq}, \quad 0 \le f_w \le 1}$$

  - Dissipation function f_w needs to be determined

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Energy balance with the two new concepts

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- Introducing the proposed models for s_m and w_m in the energy balance yields

$$\frac{1}{4}\frac{\beta_m^4}{\beta_m^2+4a}-\frac{\cos\theta}{4}\beta_m^2-\underbrace{\left[\frac{We}{12}+1-a-f_w\left(\frac{We}{12}+1-\sqrt[3]{(2+\cos\theta)(1-\cos\theta)^2/4}\right)\right]}_{=Q}=0$$

- Solution of this fourth order equation in β_m

$$\beta_m=\sqrt{\frac{2(Q+a\cos\theta)+2\sqrt{(Q+a\cos\theta)^2+4aQ(1-\cos\theta)}}{1-\cos\theta}}$$

$$Q>0 \quad\rightarrow\quad \beta_m>0$$

- Assumed relationship for the dissipation function
  - The exponents b of the Reynolds number and c of the impact parameter are determined by asymptotic analysis

$$f_w=\frac{P^c}{A+P^c}$$

$$P=We\,Re^{-b}$$

Asymptotic analysis $(a = 1)$ – Case 1

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- Assumption $(Q+\cos\theta)^2 \gg 4Q(1-\cos\theta)$ i.e. $Q \gg 4-6\cos\theta$

$$\beta_m = \sqrt{\frac{2(Q+\cos\theta)+2\sqrt{(Q+\cos\theta)^2 \cancel{+4Q(1-\cos\theta)}}}{1-\cos\theta}} \approx \sqrt{\frac{4Q}{1-\cos\theta}} \approx \sqrt{\frac{4}{1-\cos\theta}\frac{A}{A+P^c}\frac{We}{12}}$$

$$P^c = We^c Re^{-bc}$$

- Assumption $We \gg 12$

$$Q = \frac{We}{12} - f_w\left(\frac{We}{12} \cancel{+1-\sqrt[3]{(2+\cos\theta)(1-\cos\theta)^2/4}}\right) \rightarrow Q \approx (1-f_w)\frac{We}{12} = \frac{A}{A+P^c}\frac{We}{12}$$

Capillary regime $P^c < A$

$$\beta_m \approx \sqrt{\frac{We}{3(1-\cos\theta)}} \sim We^{1/2} \checkmark$$

Viscous regime $P^c > A$

Eggers (2010)

$$P = WeRe^{-2/5}$$

$$\beta_m \approx \sqrt{\frac{AP^{-c}We}{3(1-\cos\theta)}} \sim We^{(1-c)/2}Re^{bc/2} \overset{!}{=} Re^{1/5} \rightarrow c=1, b=2/5$$

Asymptotic analysis $(a = 1)$ – Case 2

- Assumption $(Q+\cos\theta)^2 \ll 4Q(1-\cos\theta)$ i.e. $Q \ll 4 - 6\cos\theta \le 10$

$$\beta_m = \sqrt{\frac{2(Q+\cos\theta) + 2\sqrt{(Q+\cos\theta)^2 + 4Q(1-\cos\theta)}}{1-\cos\theta}} \approx \sqrt[4]{\frac{16Q}{1-\cos\theta}} \approx \sqrt[4]{\frac{16}{1-\cos\theta}\frac{A}{A+P^c}\frac{We}{12}}$$

$$P^c = We^c Re^{-bc}$$

- Assumption $We \gg 12$

$$Q = \frac{We}{12} - f_w\left(\frac{We}{12} + 1 - \sqrt[3]{(2+\cos\theta)(1-\cos\theta)^2/4}\right) \rightarrow Q \approx (1-f_w)\frac{We}{12} = \frac{A}{A+P^c}\frac{We}{12}$$

Capillary regime $P^c < A$

$$\beta_m \approx \sqrt[4]{\frac{4}{3}\frac{We}{1-\cos\theta}} \sim We^{1/4} \checkmark$$

Viscous regime $P^c > A$

Clanet (2004)

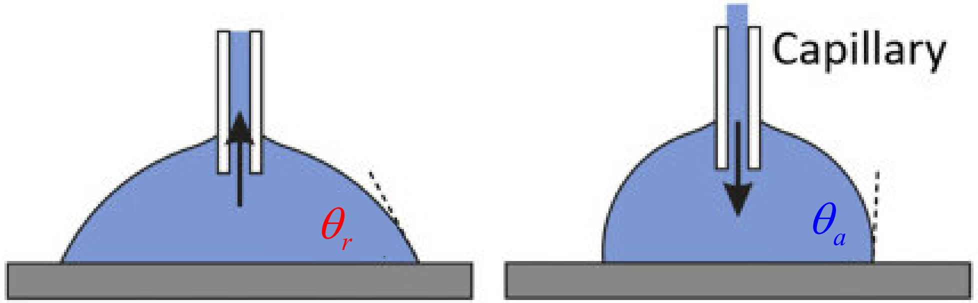
$$P = We Re^{-4/5}$$

$$\beta_m \approx \sqrt[4]{\frac{4}{3}\frac{AP^{-c}We}{1-\cos\theta}} \sim We^{(1-c)/4} Re^{bc/4} \stackrel{!}{=} Re^{1/5} \rightarrow c = 1, b = 4/5$$

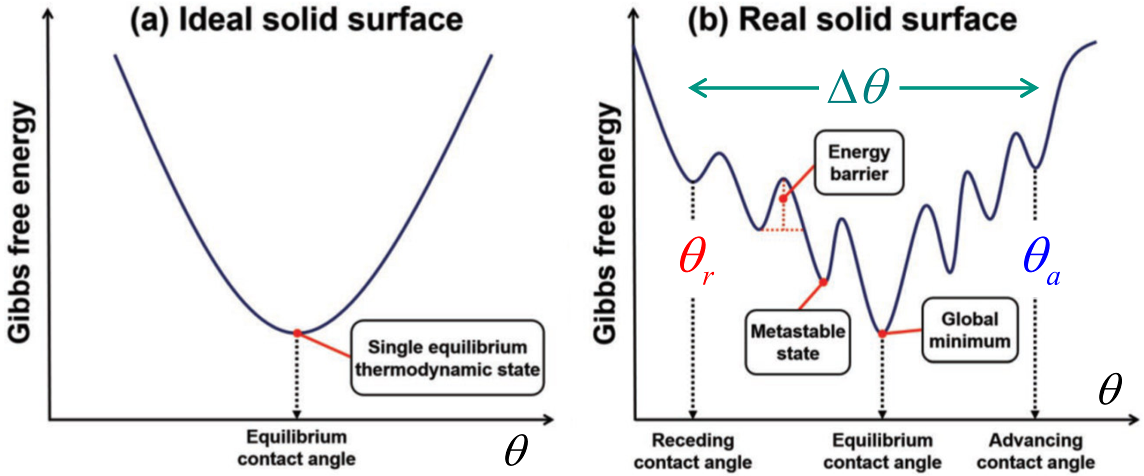
Determination of parameter A in $f_w = P/(A+P)$

- Evaluation of relative dissipation from literature data on maximum spread

$$f_w = \frac{w_m}{w_{eq}} \approx \frac{\frac{We}{12} + 1 - s_{\text{asc}}(\beta_m, a) + \frac{\cos\theta_a}{4}\beta_m^2}{\frac{We}{12} + 1 - \sqrt[3]{\frac{(2+\cos\theta_r)(1-\cos\theta_r)^2}{4}}}$$



- Which contact angle to use?
  - Equilibrium contact angle θ_{eq}
  - Advancing contact angle θ_a
  - Receding contact angle θ_r
  - Hysteresis $\Delta\theta = \theta_a - \theta_r$



📖 C.H. Kung, P.K. Sow, B. Zahiri, W. Mérida, *Advanced Materials Interfaces* **6** (2019) 1900839
📖 H.-J. Butt et al., *Current Opinion in Colloid & Interface Science* **59** (2022) 101574

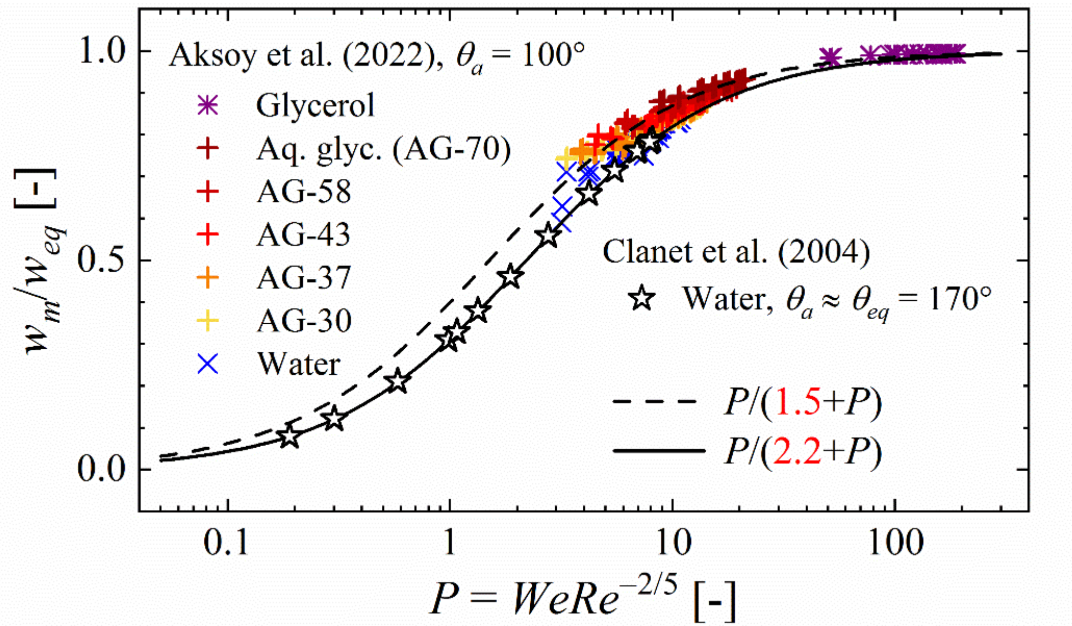
Determination of parameter A in $f_w = P/(A+P)$

- Evaluation of relative dissipation from literature data on maximum spread

$$f_w = \frac{w_m}{w_{eq}} \approx \frac{\frac{We}{12} + 1 - s_{\text{asc}}(\beta_m, a) + \frac{\cos\theta_a}{4}\beta_m^2}{\frac{We}{12} + 1 - \sqrt[3]{\frac{(2+\cos\theta_a)(1-\cos\theta_a)^2}{4}}}$$

- We use $a = 3/4$ since this gives best agreement with cylinder model

$$\rightarrow \quad s_{\text{asc}}(\beta_m) = \frac{3}{4} + \frac{1}{4}\frac{\beta_m^4}{\beta_m^2 + 4\cdot\frac{3}{4}}$$

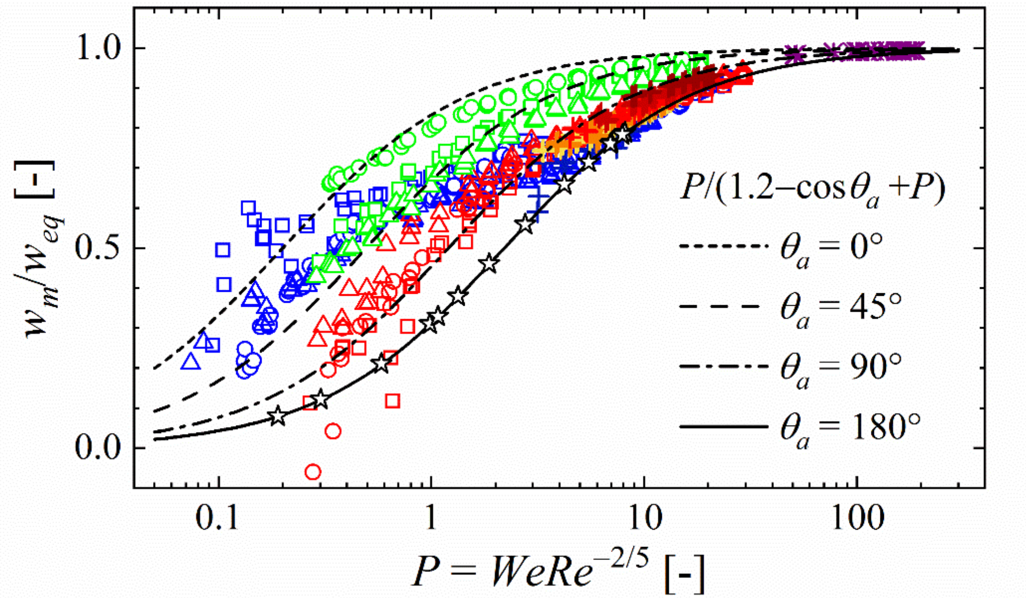


- Experimental data of Aksoy et al. (2022)
  - Seven different liquids, $57 < We < 460$, $4 < Re < 9200$, $\theta_a = 100°$ (294 data points)

📖 Y.T. Aksoy, P. Eneren, E. Koos, M.R. Vetrano, Spreading of a droplet impacting on a smooth flat surface, *Phys. Fluids* **34** (2022) 042106
📖 C. Clanet, C. Beguin, D. Richard, D. Quere, Maximal deformation of an impacting drop, *J. Fluid Mech.* **517** (2004) 199-208

Determination of parameter A (continued)

- Regime discrimination parameter A depends on the advancing contact angle θ_a
- Experimental data of Lee et al. (2016); reported θ_d and θ_{eq}, assumption $\theta_a = \theta_d$
  - Three different liquids and surfaces, $1 < We < 1200$, $40 < Re < 17\,800$, $44° < \theta_a < 123°$



- Model for the dissipation function

$$f_w = \frac{WeRe^{-2/5}}{\underbrace{1.2 - \cos\theta_a}_{=A(\theta_a)} + WeRe^{-2/5}}$$

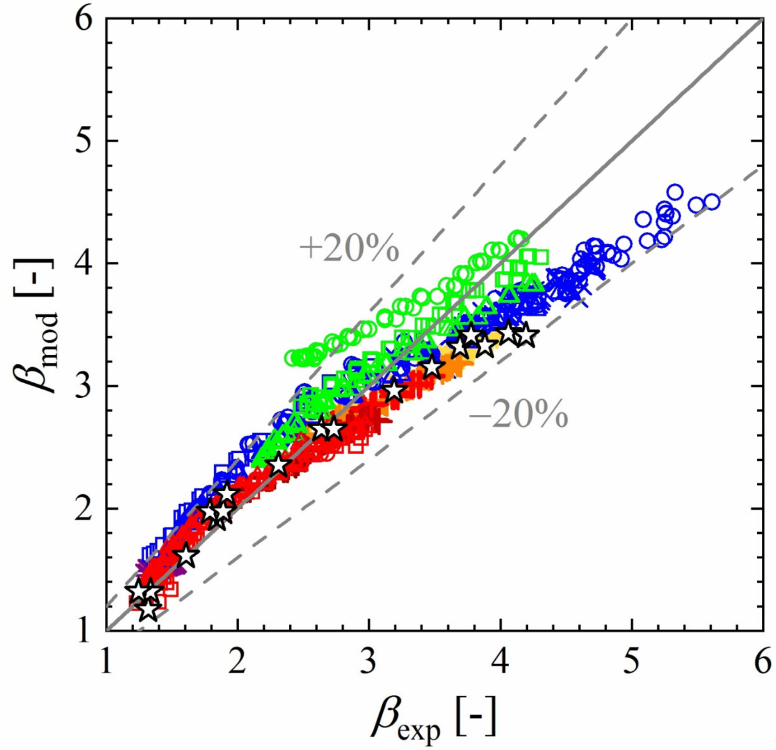
- For fixed impact parameter $P = WeRe^{-2/5}$ hydrophobic surfaces dissipate less energy upon maximum spreading as compared to hydrophilic surfaces
  $\rightarrow$ enables drop rebound

📖 J.B. Lee et al., Universal rescaling of drop impact on smooth and rough surfaces, *J. Fluid Mech.* **786** (2016) R4

Test of the proposed new model

$$\beta_m = \sqrt{\frac{2(Q+\tfrac{3}{4}\cos\theta_a)+2\sqrt{(Q+\tfrac{3}{4}\cos\theta_a)^2+4(1-\cos\theta_a)Q}}{1-\cos\theta_a}}$$

$$Q = 1-\frac{3}{4}+\frac{We}{12}-\frac{WeRe^{-2/5}}{1.2-\cos\theta_a+WeRe^{-2/5}} \times\left(\frac{We}{12}+1-\sqrt[3]{\frac{(2+\cos\theta_a)(1-\cos\theta_a)^2}{4}}\right)$$



- Parity plot against experimental data
  - Agreement is within $\pm 20\%$
  - For all experimental data it is $Q > 0$

📖 Y.T. Aksoy, P. Eneren, E. Koos, M.R. Vetrano, Spreading of a droplet impacting on a smooth flat surface, *Phys. Fluids* **34** (2022) 042106

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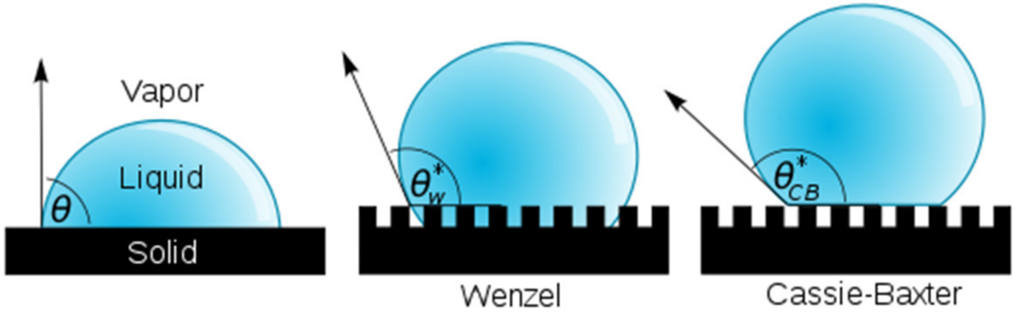
📖 C. Clanet, C. Beguin, D. Richard, D. Quere, Maximal deformation of an impacting drop, *J. Fluid Mech.* **517** (2004) 199-208

Conclusions

- Existing energy balance models for max. spread have two shortcomings
  - Gas-liquid area is not properly modelled for superhydrophobic surfaces (low β_m)
  - Models for dissipation to do not account for proper upper physical limit
- Proposal of new concepts for the two closure terms in the energy balance
  - Approximate spherical cap (asc) model for gas-liquid surface area
  - Model for dissipation that respects the upper physical limit
- Proposal of a new 'universal' energy balance model for maximum spread
  - Model comprises power law scaling for viscous regime and both capillary regimes
  - Model is explicit and thus no iteration is required
  - Dissipation function is determined from exp. data with wide ranges of We, Re, θ_a
  - Model is in good agreement with exp. with a maximum deviation of about 20%

Outlook

- Directions for model refinement
  - The current model assumes zero kinetic energy at maximum spread
  - The current model for total dissipation w_{eq} assumes zero c.a. hysteresis
  - Test model against further experimental and numerical data from literature
  - Goal: regime discrimination parameter $A = A(\theta_a, \Delta\theta)$
    $\rightarrow$ measurement of the advancing and the receding contact angle is required
- Extend model to surfaces with regular roughness
  - Wenzel and Cassie-Baxter wetting states



https://en.wikipedia.org

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📖 Y.T. Aksoy, P. Eneren, E. Koos, M.R. Vetrano, Spreading of a droplet impacting on a smooth flat surface, *Phys. Fluids* **34** (2022) 042106
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