Numerische Analyse der Zweiphasenströmung und der Wärmeübertragung in geschlossenen Thermosiphon-Sonden

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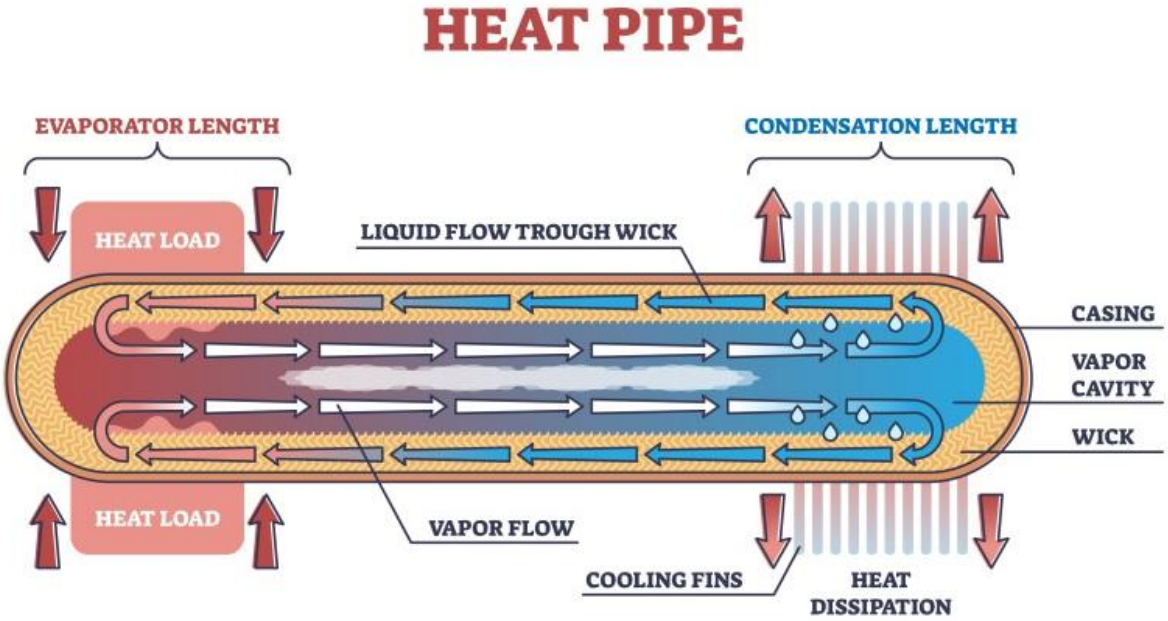
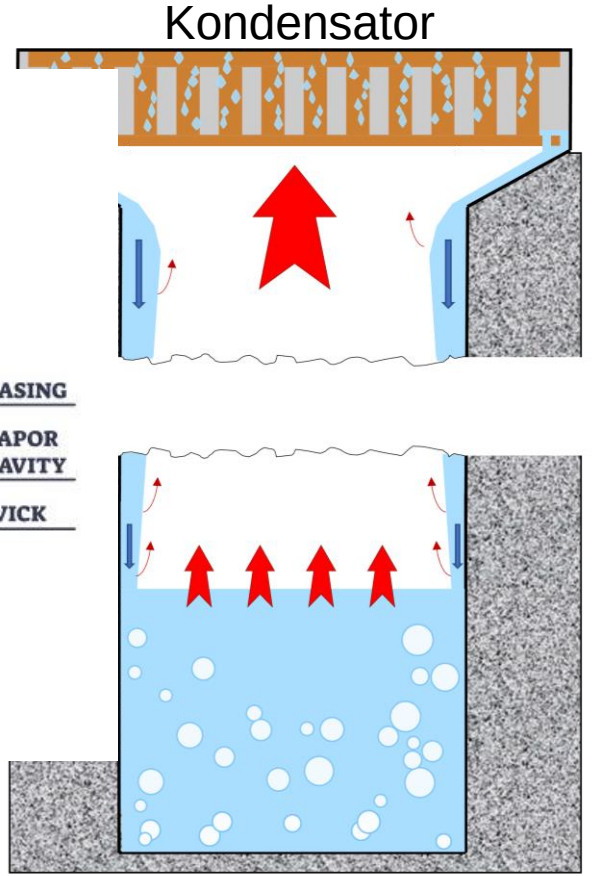
Thermosiphon-Sonden





Quelle: https://www.global.dnp/biz/column/detail/10162360_4117.html

Motivation

- Innovative Anwendung in Geothermie
  - Kein Hilfsaggregat (z.B. Pumpe) erforderlich
  - Effizienter Wärmetransport durch latente Wärme
- Herausforderungen
  - Effekte wie Dry-out und Flooding, CO_2-Gasreinheit, komplexes Strömungsverhalten in der Sonde, Grenzflächeneffekte usw.
- Ziel und Lösungsansatz
  - Optimierung der Thermosiphon-Sonde, Sicherstellung eines sicheren Betriebs
  - Numerische Berechnung mit verifiziertem Modell (OpenFOAM)

Agenda

- 2D-Filmmodell in OpenFOAM
  - Simulation dünner Flüssigkeitsfilme im Bereich zehntel-Millimeter
  - 2D-Flachwassergleichungen und Transportgleichungen für Energie
- Verifizierung
  - Nusselt'sche Wasserhauttheorie
- Ergebnisse und Parameteruntersuchung

Mathematisches Modell für Filmströmung

- Massenerhaltung

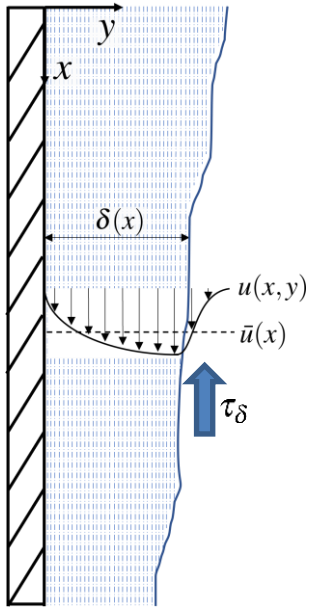
$$\frac{\partial(\delta\rho)}{\partial t} + \nabla_s \cdot (\delta\rho\,\vec{u}) = S_\delta$$

- Impulserhaltung

$$\frac{\partial(\delta\rho\,\vec{u})}{\partial t} + \nabla_s \cdot (\delta\rho\,\vec{u}\vec{u}) = -\nabla_s(\delta p) + \nabla_s \cdot (\delta\,\tau) + \delta\rho\,\vec{g}_s + \vec{f}_\sigma + S_{\delta,\mathrm{I}}$$

- Energieerhaltung

$$\frac{\partial(\delta\rho h)}{\partial t} + \nabla_s \cdot (\delta\rho\,\vec{u}h) = \nabla_s \cdot (\delta\lambda\nabla_s T) + q_{\mathrm{int}} + S_{\delta,\mathrm{E}}$$

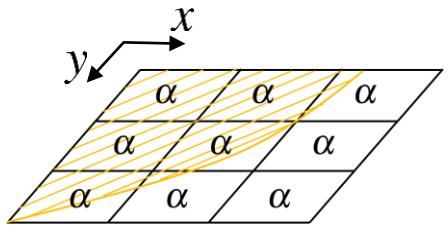


$\vec{u}$ ist die wandtangentiale gemittelte Filmgeschwindigkeit.

Kontaktwinkel-Modell

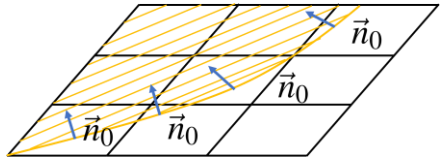
- Grenzflächennormalvektor

$$\vec{n}_0 = \frac{\nabla_s \alpha}{|\nabla_s \alpha|}, \quad \nabla_s \alpha = \left(\frac{\partial \alpha}{\partial x}, \frac{\partial \alpha}{\partial y} \right), \quad \alpha = \delta \cdot \frac{A_{\text{cell}}}{V_{\text{cell}}}$$



- Anfangskontaktwinkel und Wandnormalvektor

$$\vec{n}_0 \cdot \vec{n}_{\text{wall}} = \cos\theta_0$$



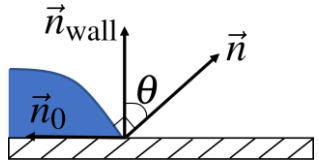
- Korrigierter Kontaktwinkel

$$\vec{n} = a \cdot \vec{n}_0 + b \cdot \vec{n}_{\text{wall}},$$

$$\cos\theta = \vec{n} \cdot \vec{n}_{\text{wall}}$$

$$a = \frac{\cos(\theta_0 - \theta) - \cos\theta_0 \cos\theta}{1 - \cos^2\theta_0}$$

$$b = \frac{\cos\theta - \cos\theta_0 \cos(\theta_0 - \theta)}{1 - \cos^2\theta_0}$$



Kontaktwinkelkraft

- Krümmung

$$\kappa = -\nabla_s \cdot \vec{n}$$

- Resultierende Kontaktwinkelkraft

$$\vec{f}_\sigma = \sigma \kappa \nabla_s \alpha$$

- In Impulsgleichung

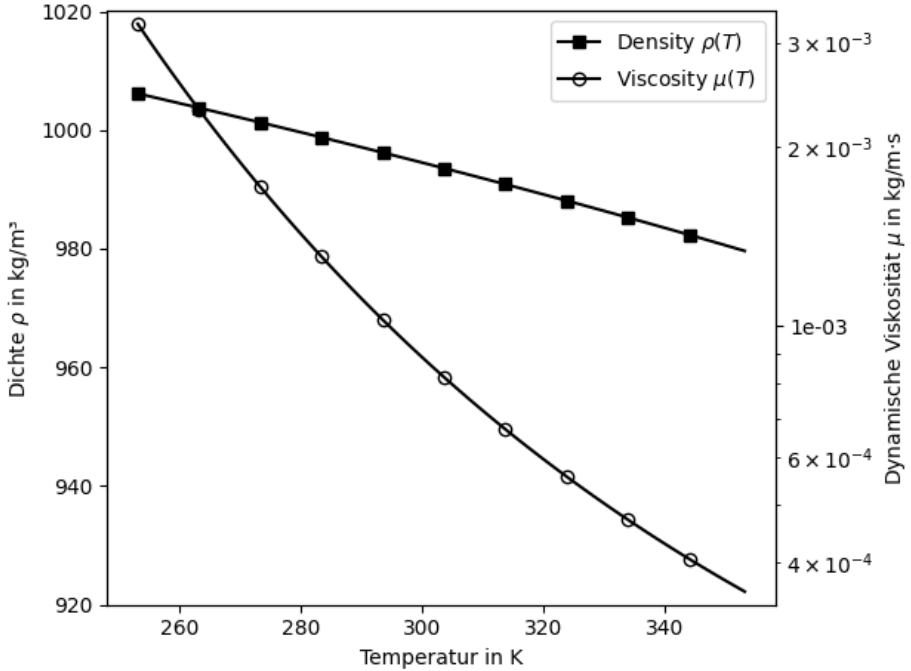
$$\frac{\partial(\delta\rho\,\vec{u})}{\partial t} + \nabla_s \cdot (\delta\rho\,\vec{u}\vec{u}) = -\nabla_s(\delta p) + \nabla_s \cdot (\delta\,\tau) + \delta\rho\,\vec{g}_s + \boxed{\vec{f}_\sigma} + S_{\delta,\mathrm{I}}$$

Stoffeigenschaften

- Materialeigenschaften sind nach NSRDS (NIST) empirisch bestimmt, z.B. für H_2O
- Dichte: NSRDS5
- Dyn. Viskosität: NSRDS2

$$\rho(T) = \frac{a}{b^{1+(1-T/c)^d}}$$

$$\mu(T) = \exp\left(a + \frac{b}{T} + c\ln T + dT^e\right)$$



Verifikation: 1D-Filmströmung

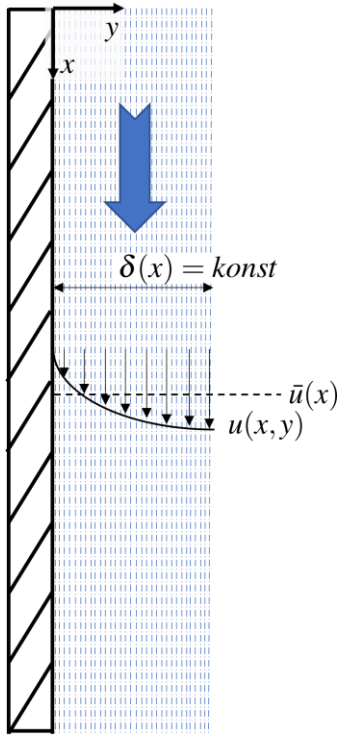
- Annahmen:
  - Stationär, laminar und inkompressibel
- Analytische Lösung nach Nusselt'scher Wasserhauttheorie:

$$\delta = \left(\frac{3}{4} \frac{\nu^2 \mathrm{Re}}{g} \right)^{1/3}$$

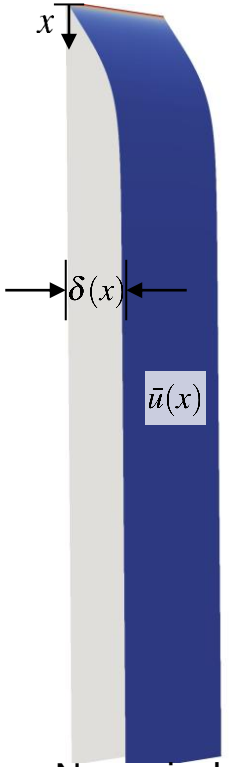
- Reynoldszahl und Kapitza-Zahl

$$\mathrm{Re} = \frac{4\Gamma}{\mu} \qquad Ka = \frac{\sigma}{\rho\, g^{1/3} \nu^{4/3}}$$

- Eindimensionale Diskretisierung

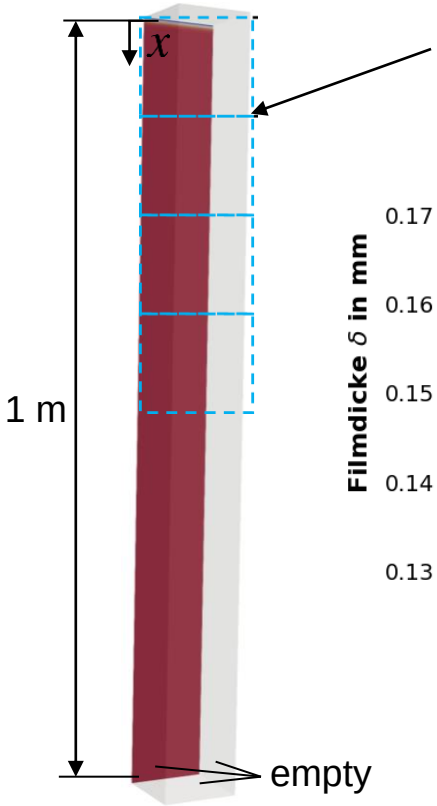


Analytisch

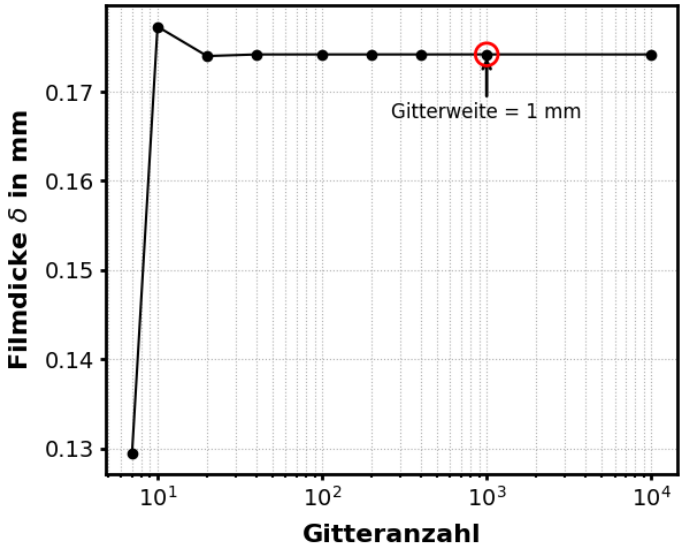


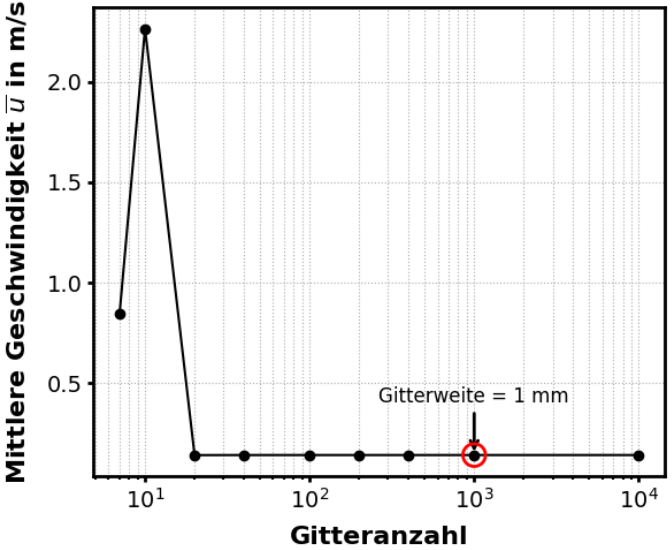
Numerisch (1D)

Gitterkonvergenzstudie

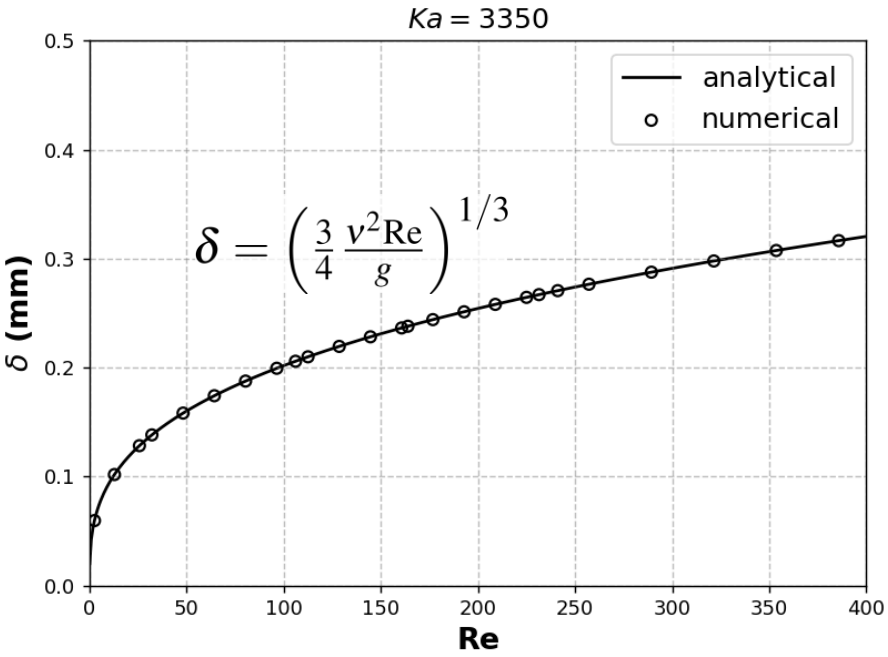


An der Stelle: x = 0,1 m, Re ~ 96

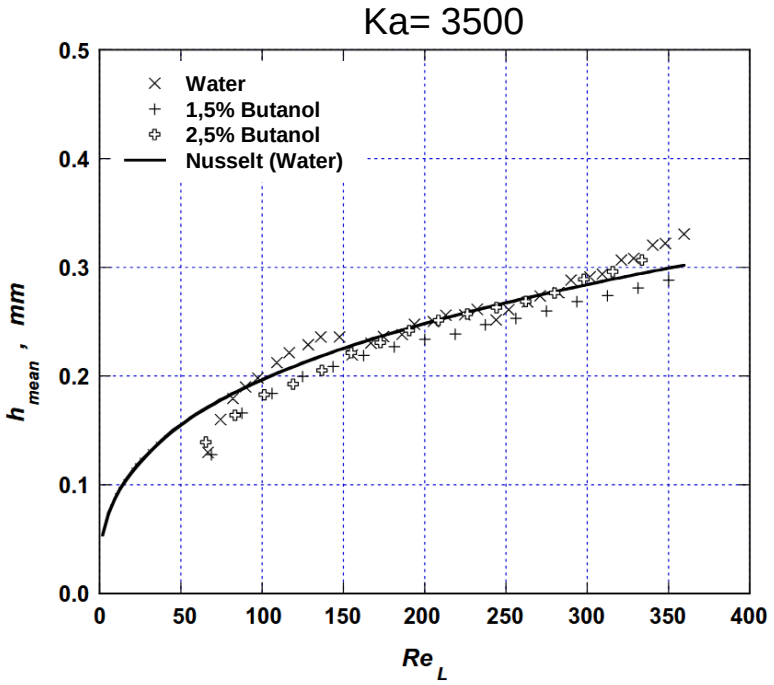




Verifizierung des Solvers



Numerische Berechnung

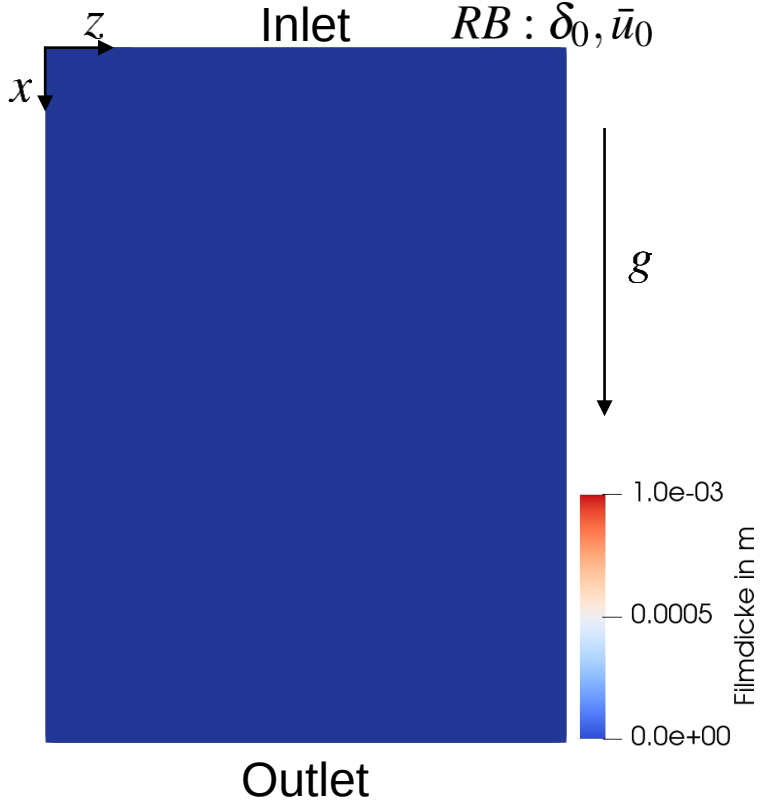


Experimente aus Literatur [Drosos 2004]

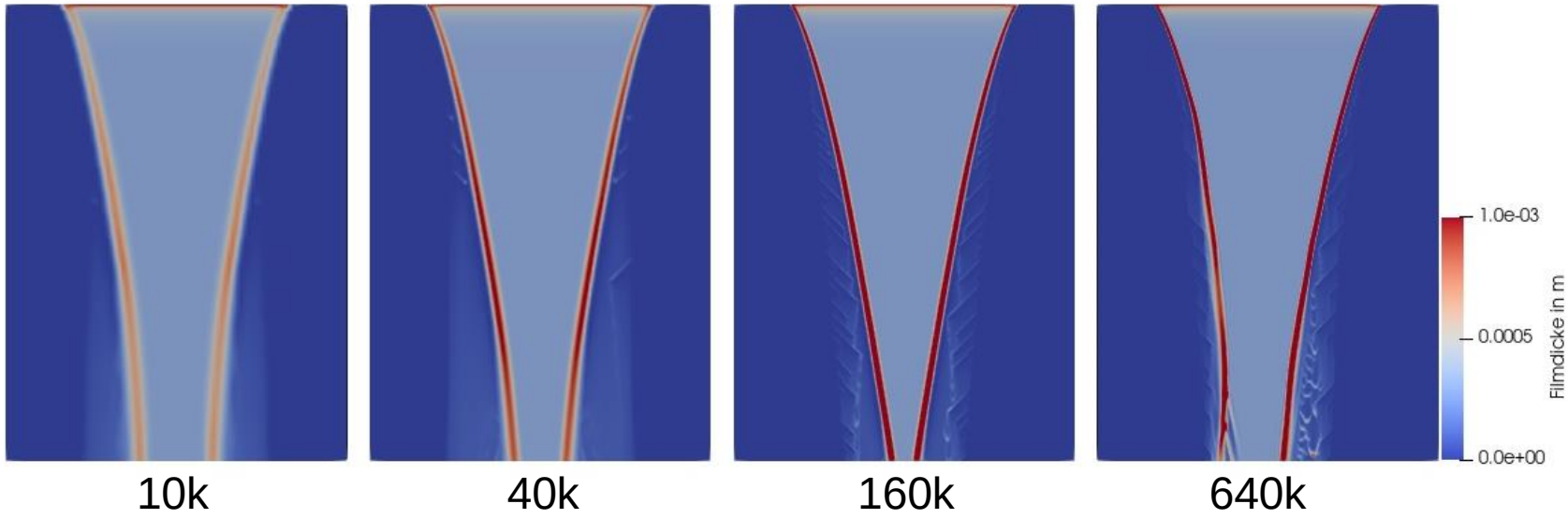
Drosos et al., Int. J. Multiphase Flow, 2004

Verifikation: Film auf vertikaler Platte

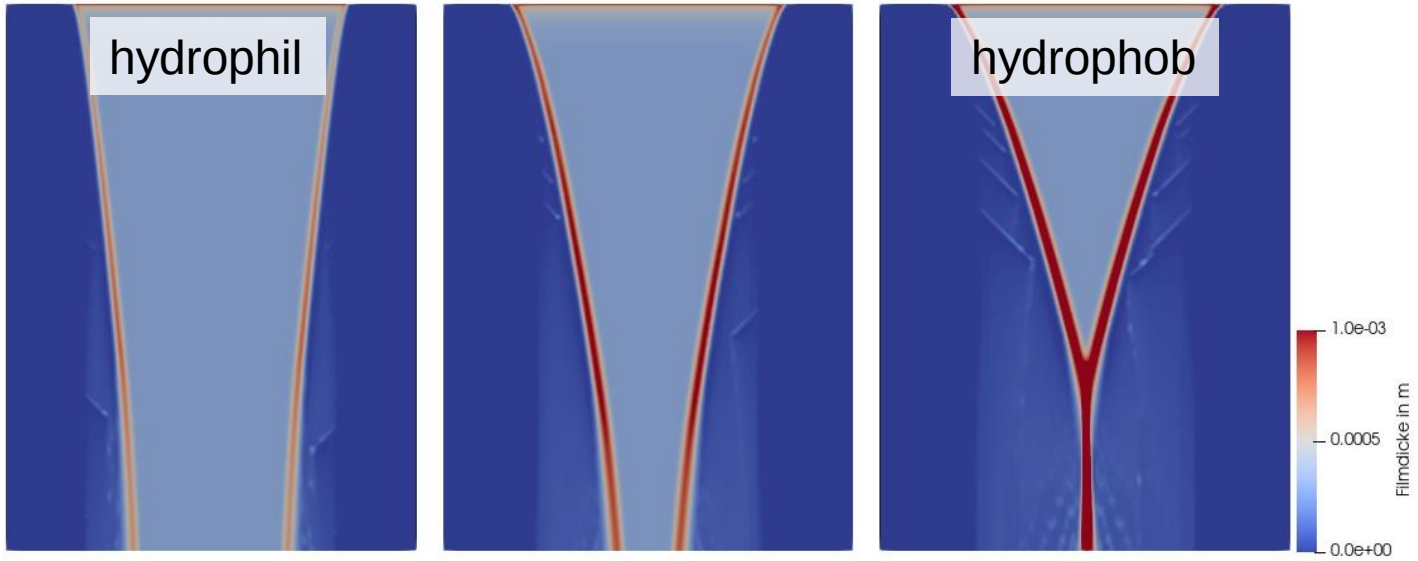
- Einflussgrößen
  - Gitterfeinheit
  - Benetzbarkeit
  - Massenstrom
  - Gravitation



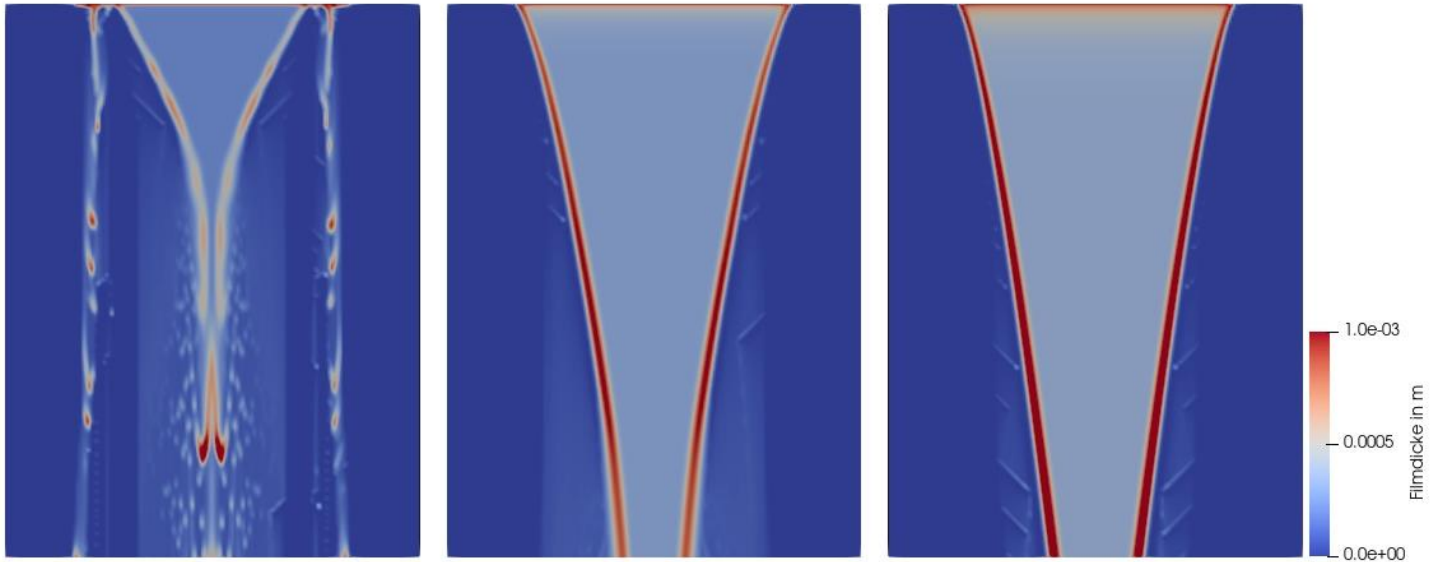
Gitterfeinheit



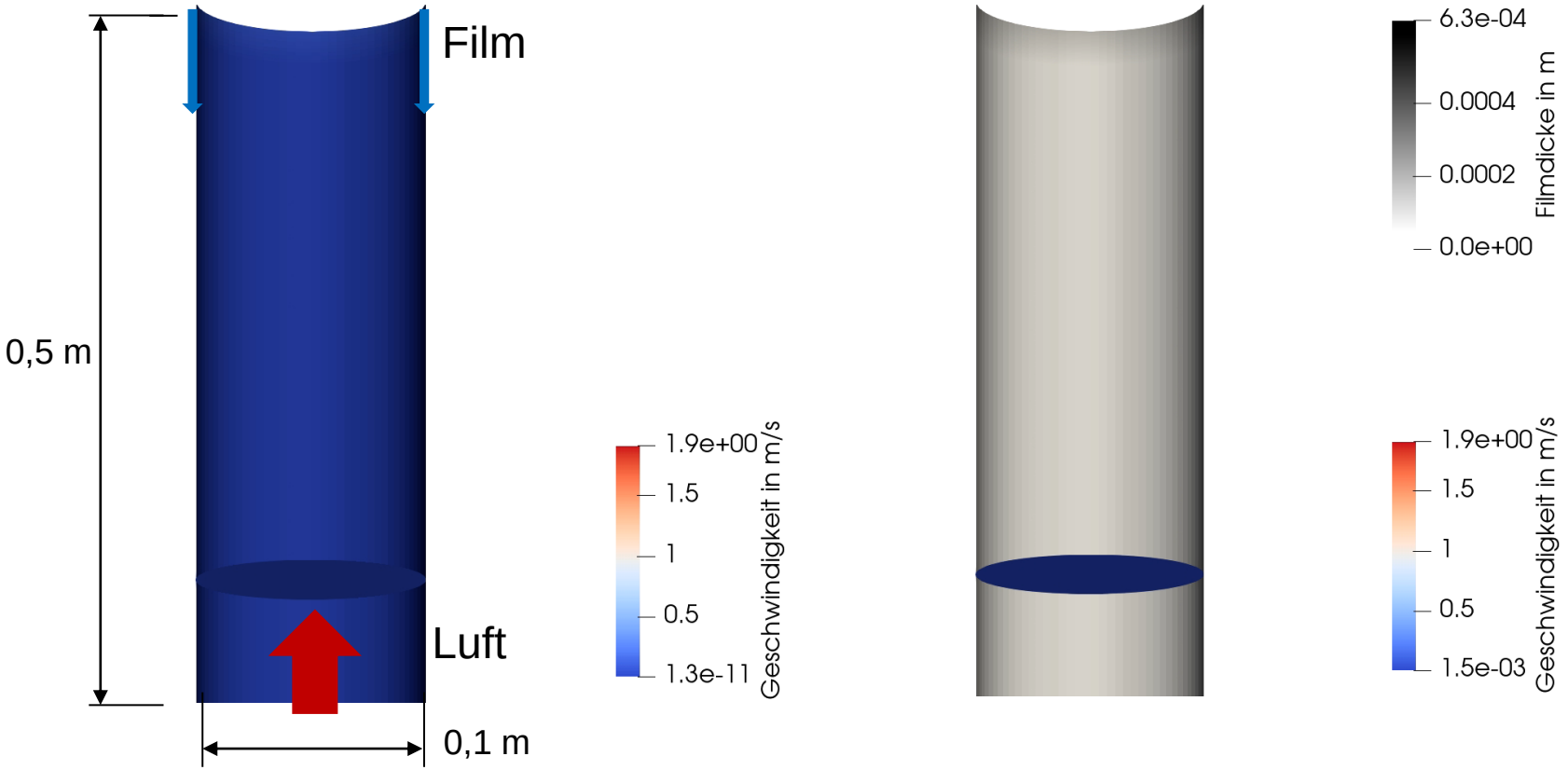
Benetzbarkeit



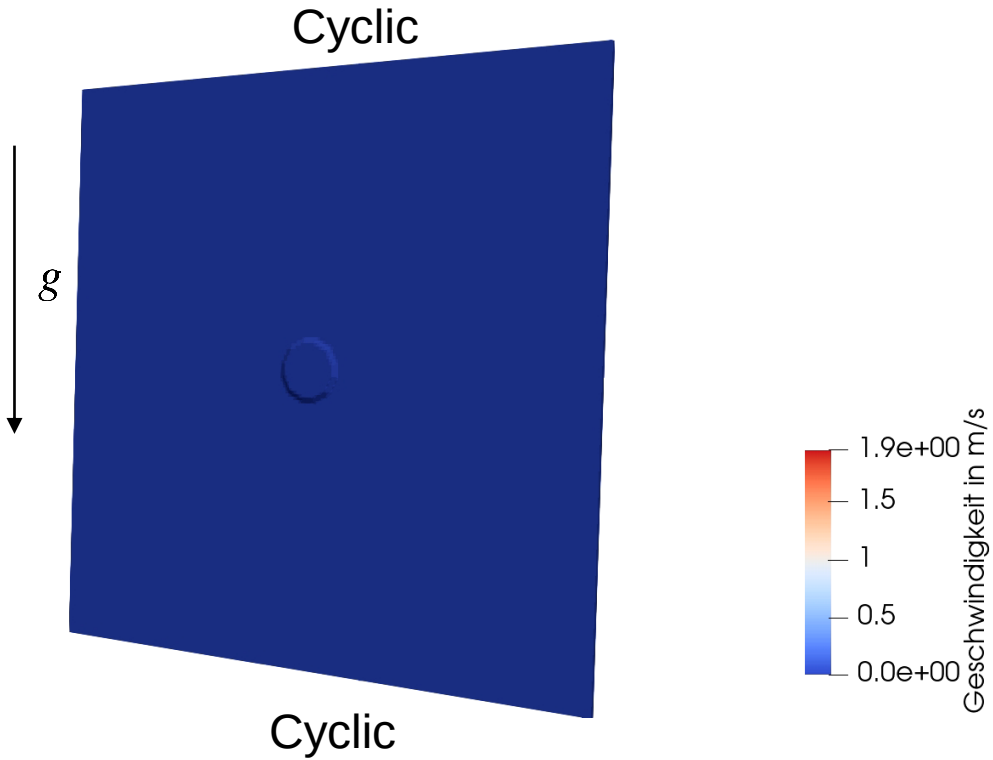
Massenstrom



Zweiphasenströmung

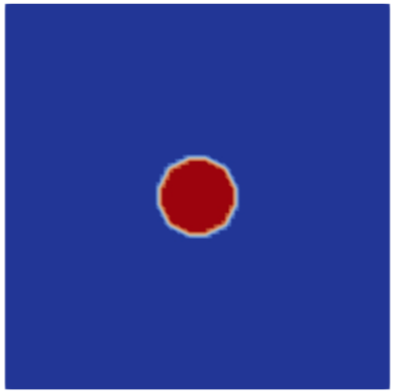


Tropfen auf vertikale Platte

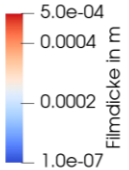


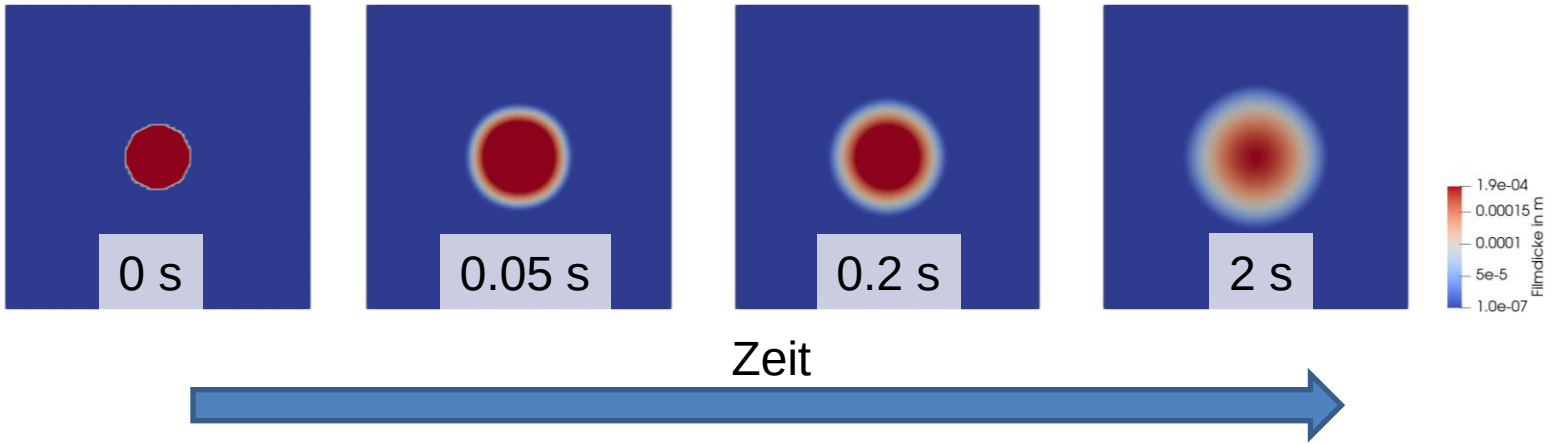
Tropfen auf horizontale Platte

- Geometrie: 40 * 40 mm²
- Anfangsfilmdicke: 0.5 mm
- Radius: 4 mm
- Form: zylindrisch

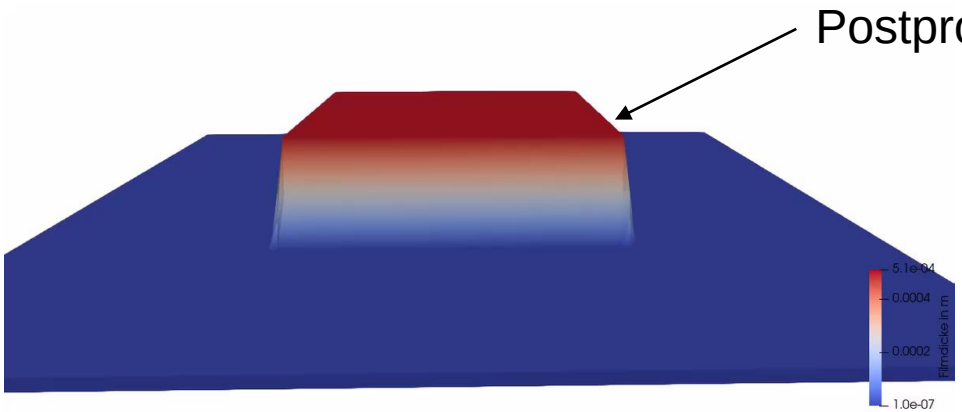


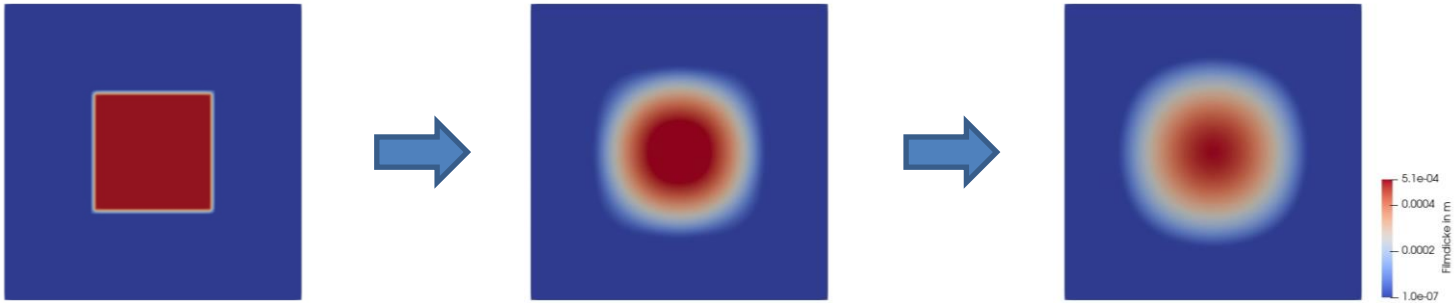
$\vec{g} = 0$





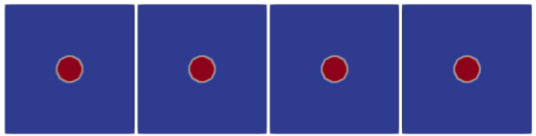
Andere Anfangsbedingungen

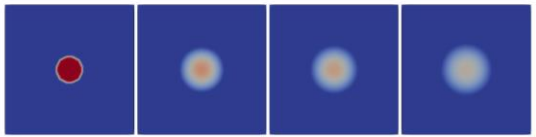


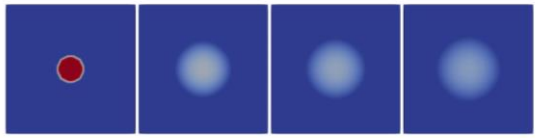


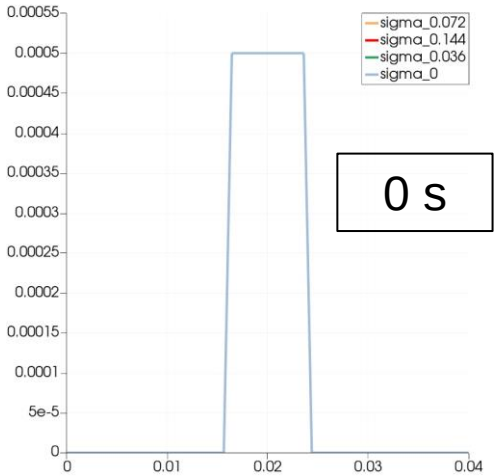
Oberflächenspannung

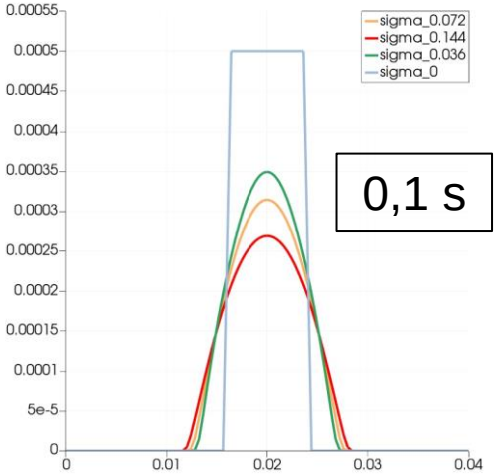
$\sigma = 0 \quad 0.036 \quad 0.072 \quad 0.144\,\mathrm{N/m}$

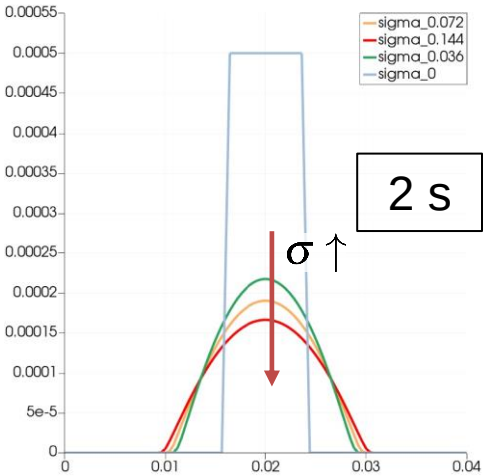






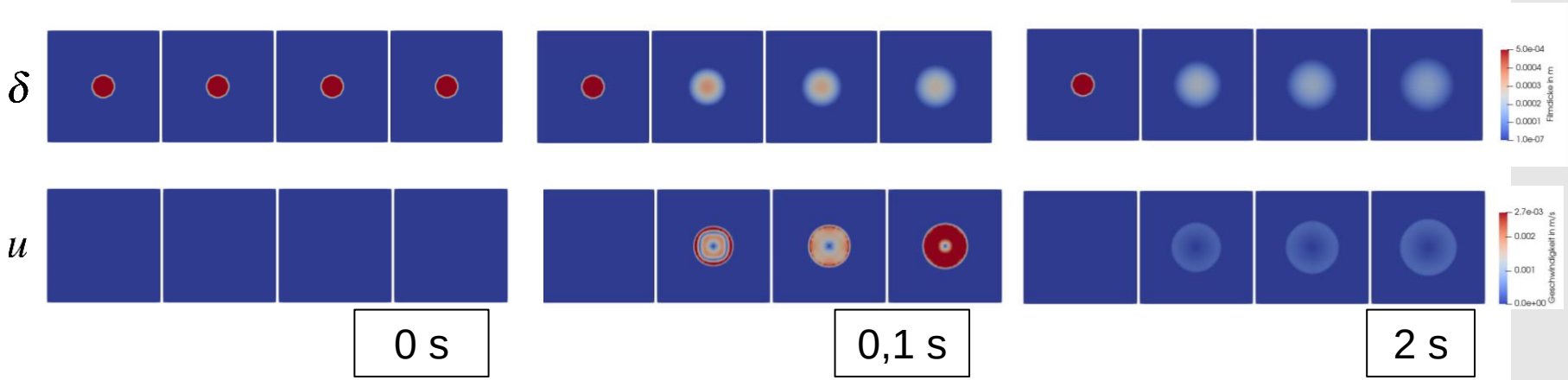






Zeit

Parasitic Currents



- Offene Fragen:
  - Wie lässt sich dieses Phänomen vermeiden?

Zusammenfassung und Ausblick

- Zusammenfassung
  - Verifizierung der 2D-Filmmodells
  - Kontaktwinkel, Oberflächenspannung, Massenstrom, Gravitation

- Ausblick
  - Validierung
  - Implementierung des Phasenwechselmodells
  - Berechnung des realen Szenarios der Thermosiphon-Sonde

Vielen Dank!

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