Reynolds Number and Humidity Dependency of Dropwise Condensation in Moist Convective Airflows

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DLR

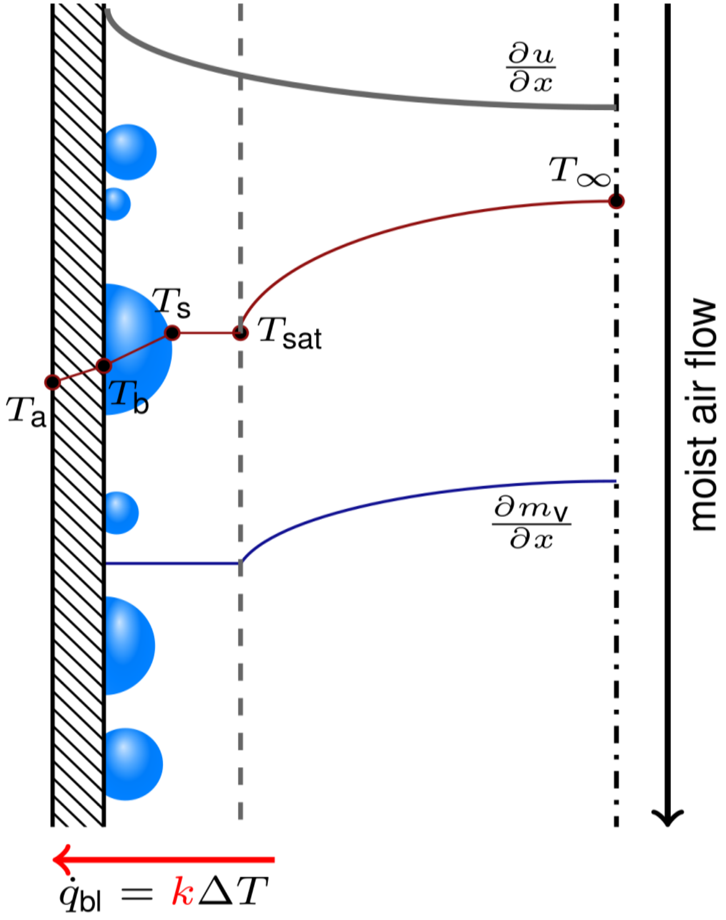
MOTIVATION

Dropwise condensation
- fogging on windows or panes causes problems
- functional restriction of optical sensors
- decrease or increase of heat exchanger efficiency
- defogging of a wind shield in an electronic vehicle results in shorter driving range
- condensation at the outer aircraft structures leads to insulation reduction and corrosion

Research objectives
- film vs. dropwise condensation
- **characterisation of the mutual interplay of flow structures and mass/heat transport mechanism**
- **scaling of heat and mass transfer**
- developing of prediction / numerical models
- impact of droplet formation and dynamics on the heat transfer

CONVECTIVE AIR FLOW WITH PHASE TRANSITION

Global heat transfer



Navier-Stokes

$$\partial_t' \vec{u}' + \vec{u}'\nabla'\vec{u}' = -\nabla' p' - \frac{1}{\mathrm{Re}}\nabla'^2\vec{u}' - \frac{\mathrm{Gr}_{hc}}{\mathrm{Re}^2}(T' - T_0')\vec{e}_z$$

heat transfer

$$\partial_t' T' + \vec{u}'\nabla' T' = \frac{1}{\mathrm{Pr}\,\mathrm{Re}}\nabla' T' + \frac{1}{\mathrm{Ja}}\partial_t'\rho_v'$$

diffusion

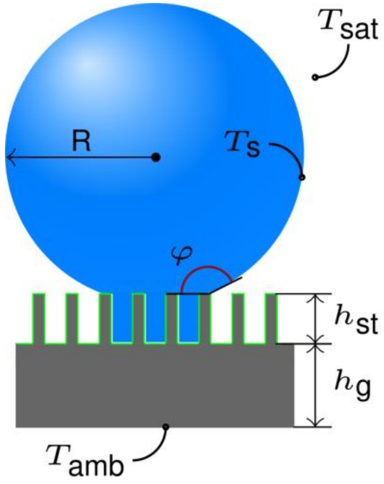
$$\partial_t'\rho_v' + \vec{u}'\cdot\nabla'\rho_v' = \frac{1}{\mathrm{Sc}\,\mathrm{Re}}\nabla'^2\rho_v + \frac{1}{\mathrm{Ja}}\dot{\rho}_v'$$

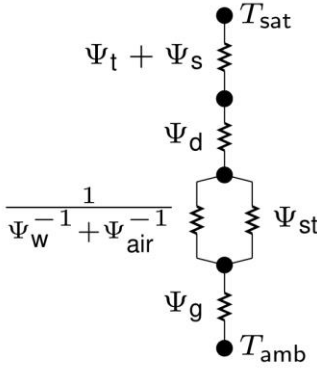
characteristic numbers

$$\mathrm{Gr}_{hc} = \frac{g\beta_T(T_h - T_c)L^3}{\nu^2} \qquad \mathrm{Ja} = \frac{(T_h - T_c)c_p}{h_v}$$

$$\mathrm{Pr} = \frac{\nu\rho c_p}{\lambda} \qquad \mathrm{Sc} = \frac{\nu}{D} \qquad \mathrm{Re} = \frac{U_{ein}L}{\nu}$$

local heat transfer on a surface





thermal resistance : $\Psi_t = 2\,T_s\,\sigma / R\,h_v\,\varrho_v\,\dot{Q}$

droplet surface : $\Psi_s = 1/\alpha_s 2\,\pi\,R^2\,(1 - \cos(\varphi))$

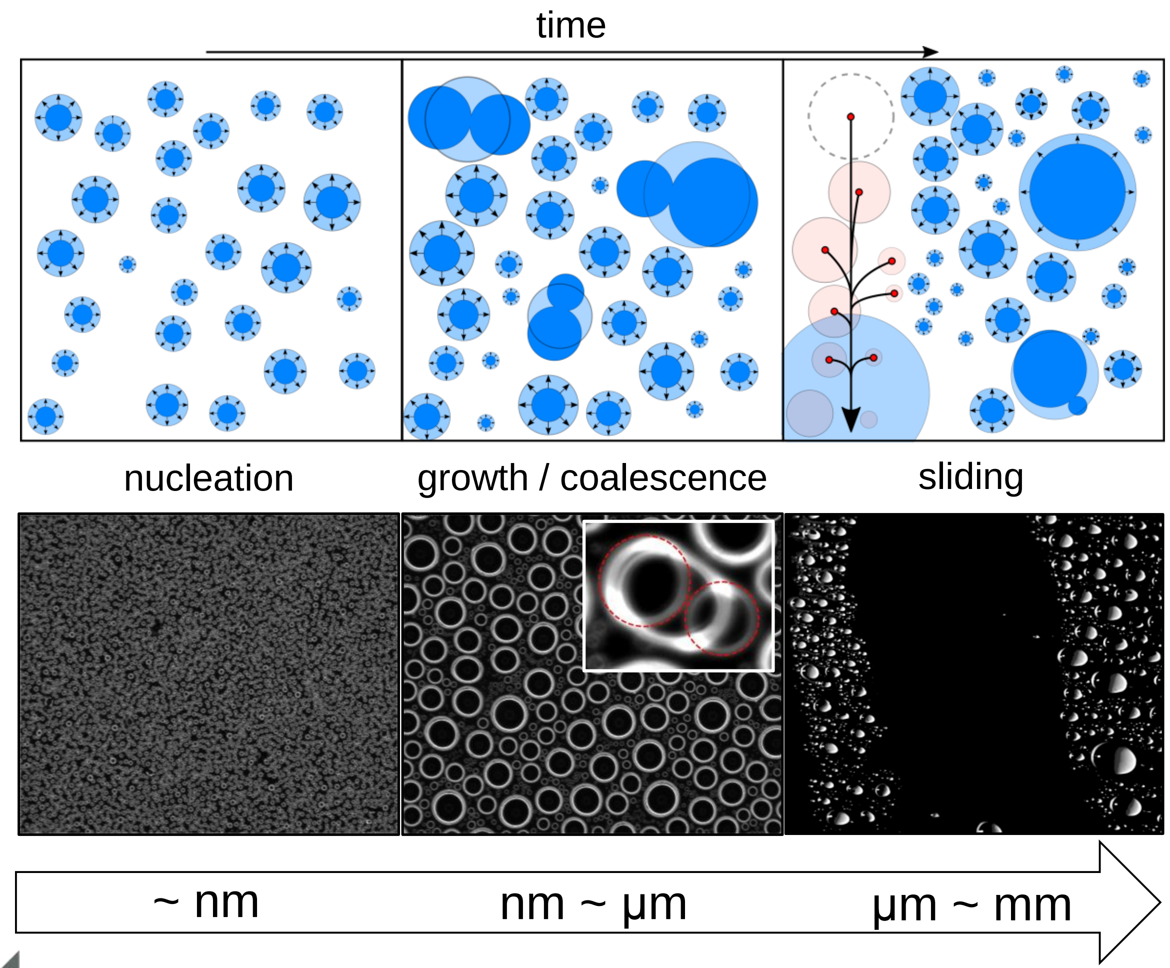
droplet : $\Psi_d = \Theta / 4\pi R \lambda_w \sin(\varphi)$

surface structure : $(1/\Psi_{st} + 1/\Psi_w + 1/\Psi_{air})^{-1}$

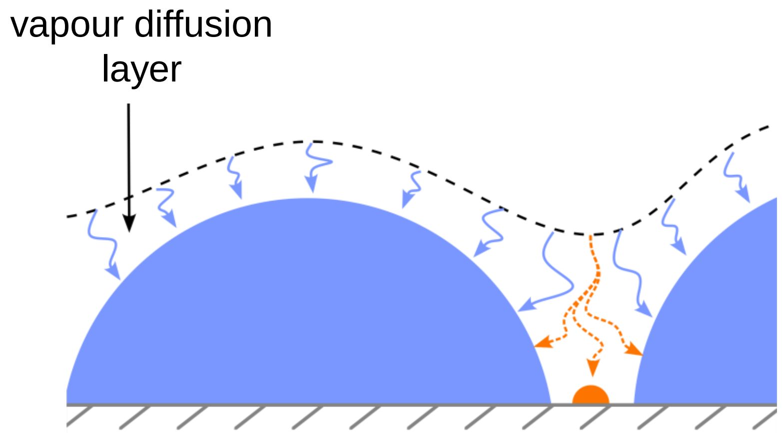
glass pane : $\Psi_g = h_g / \pi R^2 \sin^2(\varphi)\lambda_g$

DROPWISE CONDENSATION ON A VERTICAL WALL

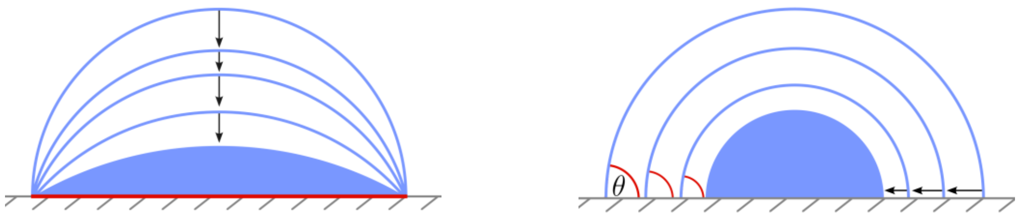
multiscale characteristics



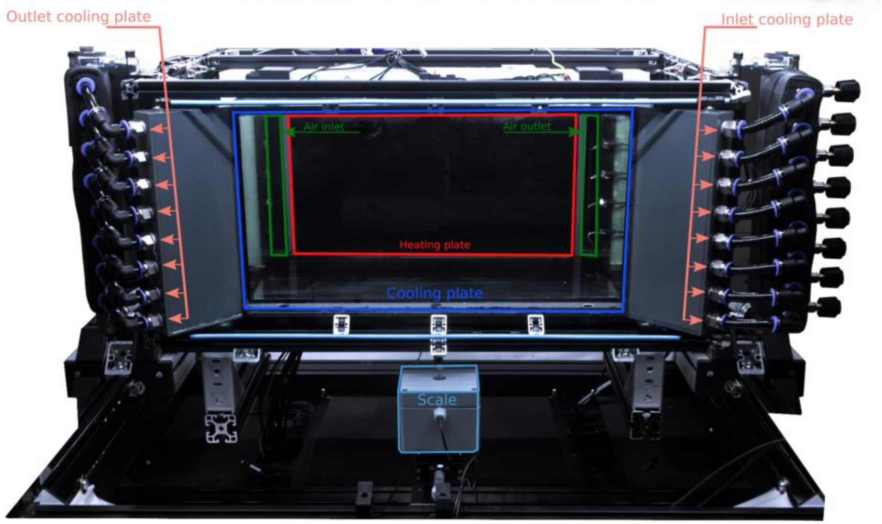
droplet growing

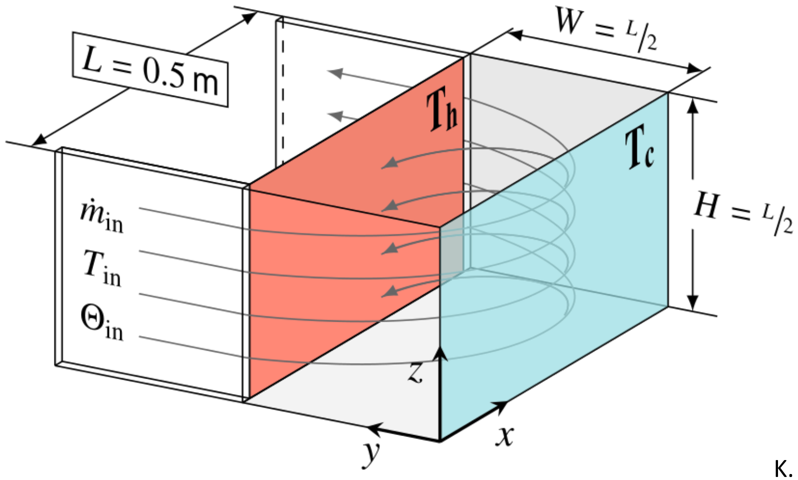


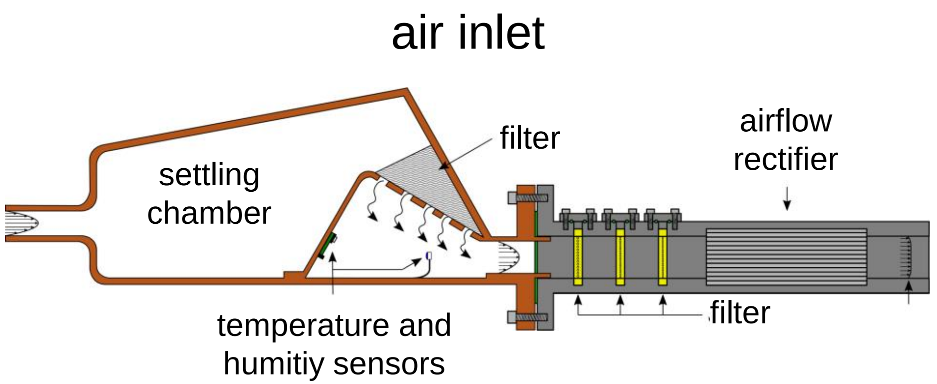
modes of evaporation

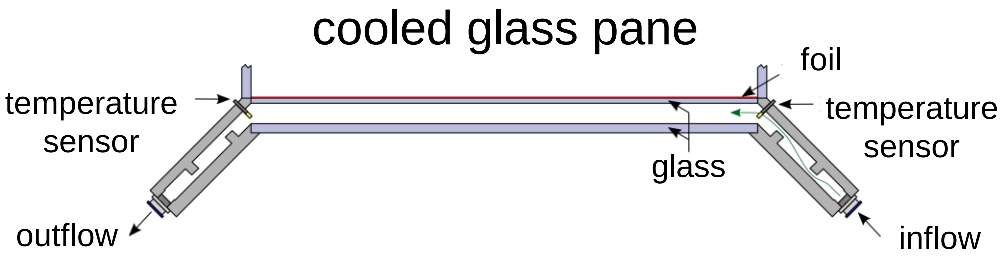


EXPERIMENTAL SETUP









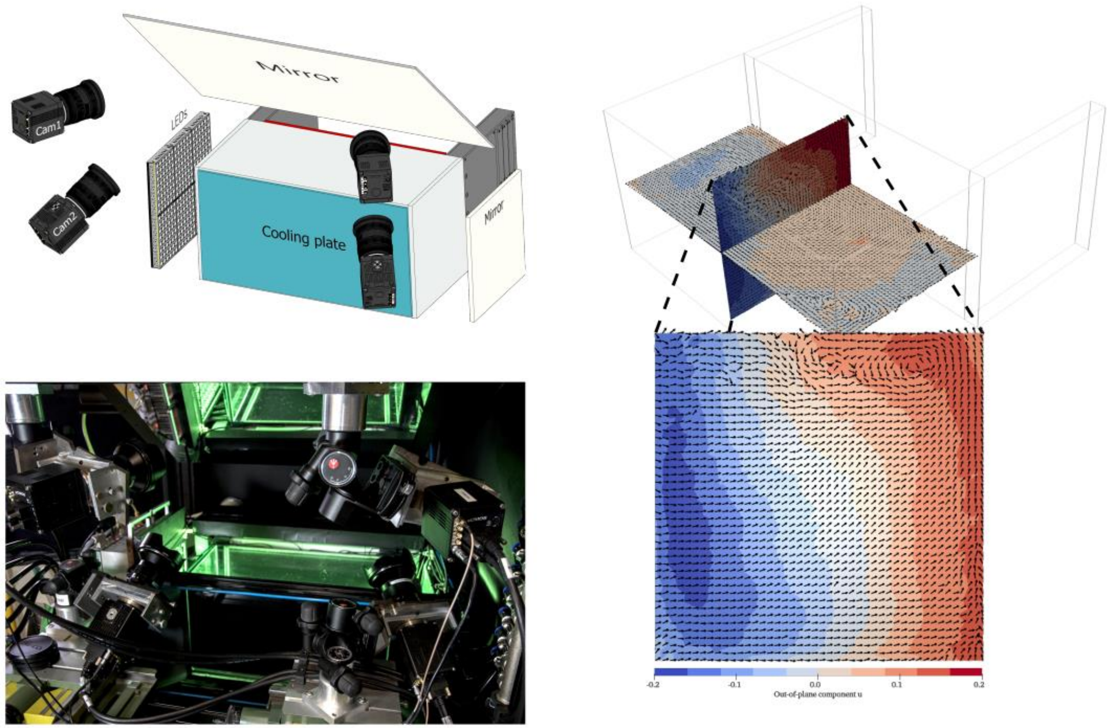
boundary conditions

- isothermal front and back
- top, bottom and side walls are adiabatic
- constant temperature, humidity and volume flow at the inlet

K. Niehaus. A. Westhoff and C. Wagner (2021), *Characterization of a Mixed Convection Cell Designed for Phase Transition Studies in Moist Air,* 22nd STAB/DGLR Symposium on New Results in Numerical and Experimental Fluid Mechanics XIII, 483-493. Springer Nature.

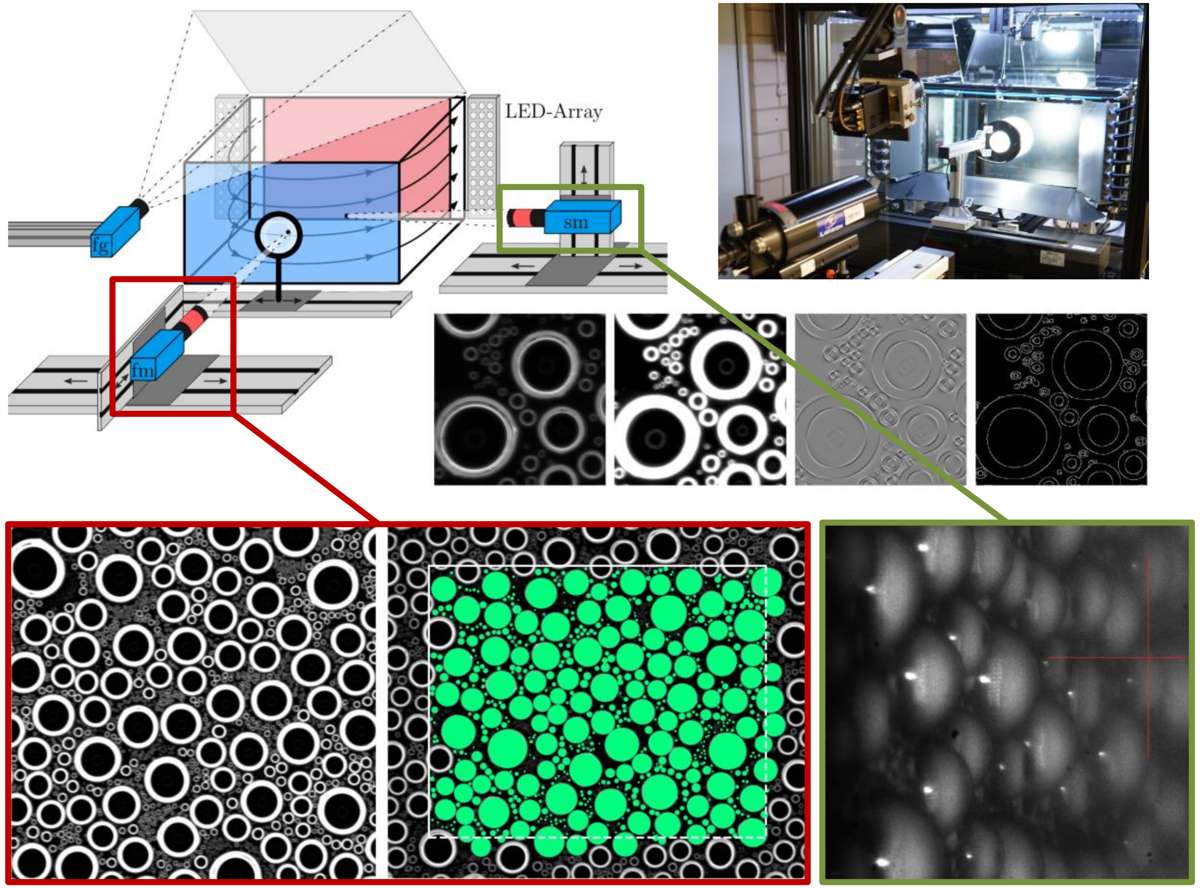
OPTICAL MEASUREMENTMETHODS

tomographic particle image velocimetry



K. Niehaus, Experimentelle Untersuchung des Skalenverhaltens bei Kondensation und Verdampfen in einem generischen Fahrzeugscheinwerfer (2023), PHD Thesis

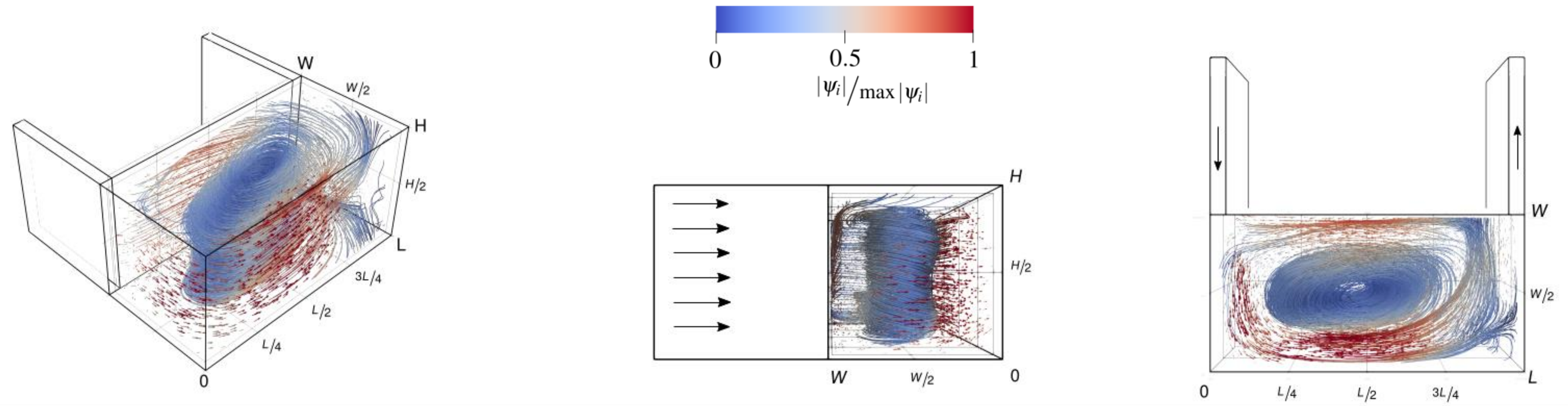
automatic droplet detection



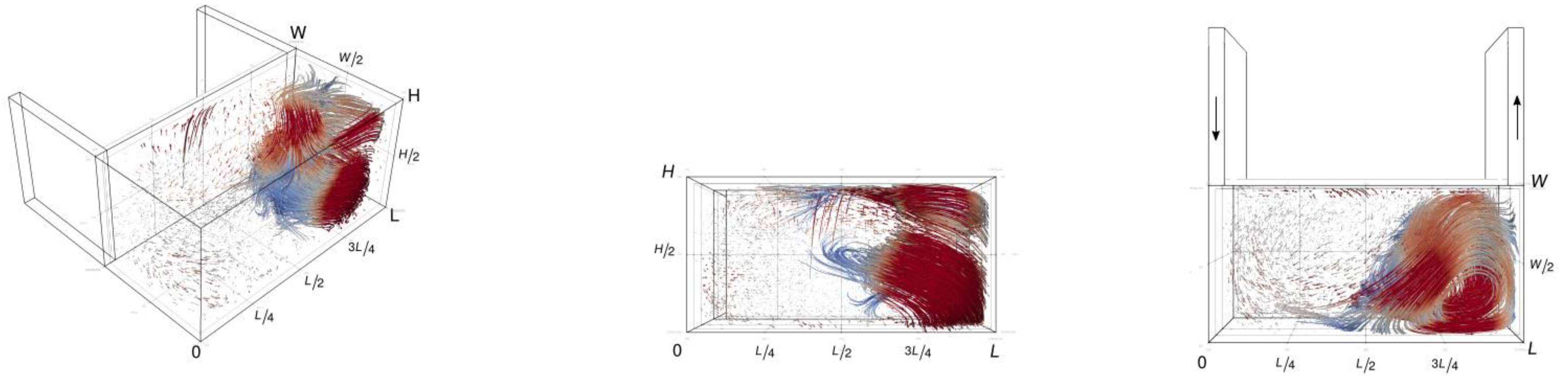
M.-C. Volk, Automatisierte Analyse des Wachstums von oberflächenbehafteten Wassertropfen in Mischkonvektion mit Phasenübergang (2023), Master Thesis

COHERRENT FLOW STRUCTURES

POD MODE 1



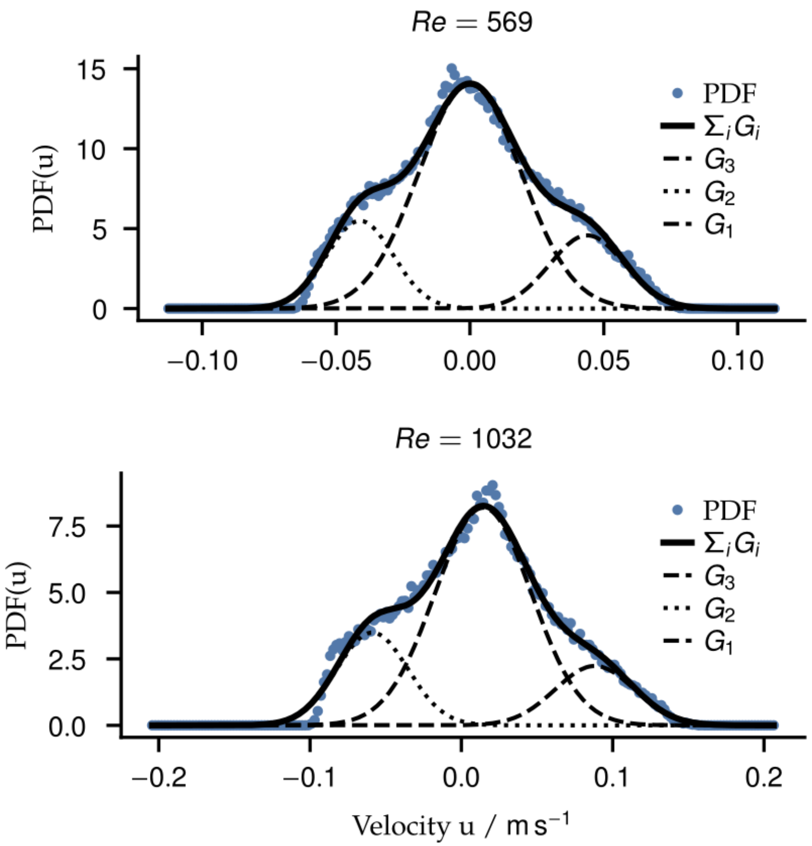
POD MODE 2



Two predominant large–scale flow structures (>90% kinetic energy)

LARGE-SCALE FLOW CHARACTERISATION

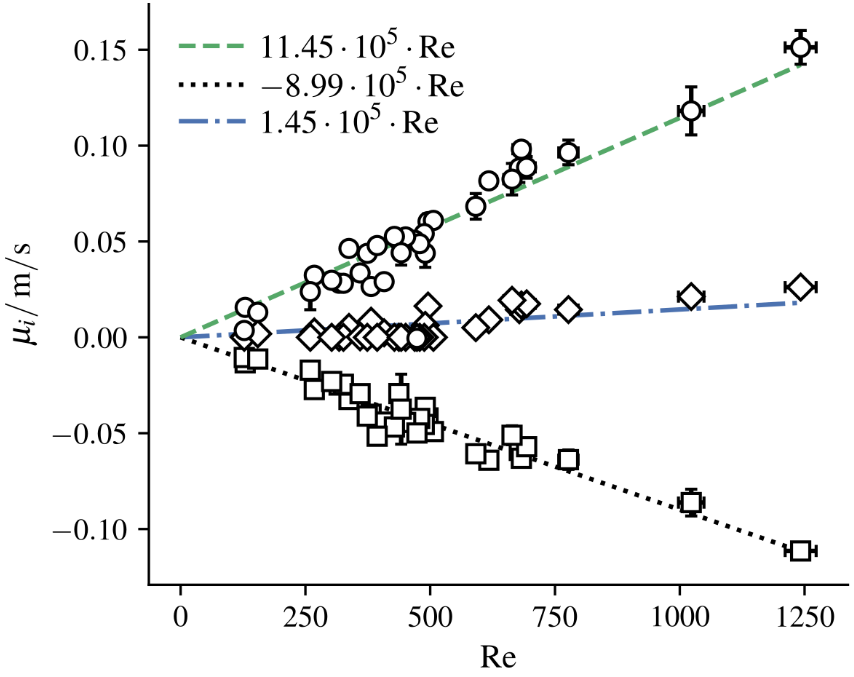
$$Gr_{hc} = 8.5 \times 10^7$$



parameter range

$$130 \leq Re \leq 1270$$

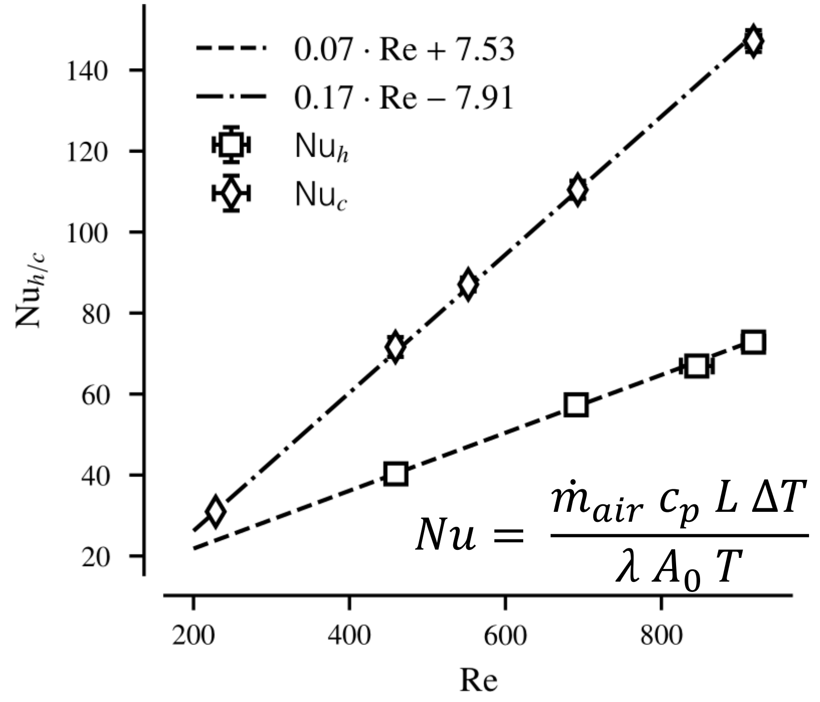
$$0 \leq Gr_{hc} \leq 1.5 \times 10^8$$



- Gaussian functions representing flow of LSC, near heated wall and near cooled wall
- mean velocity scales linear with Re
- velocity ratio $\mu_c/\mu_h = 0.78(3)$ is constant → forced flow
- time-averaged large-scale flow structures are a function of Re and Gr-independent

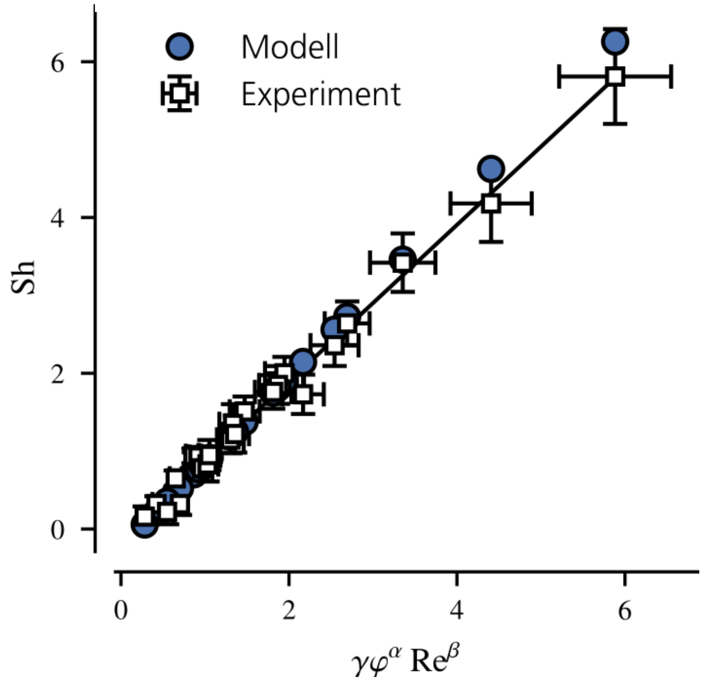
SCALING GLOBAL MASS AND HEAT TRANSFER

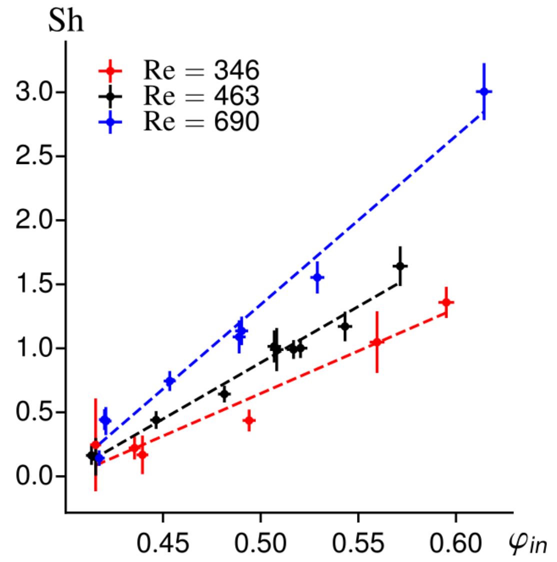
sensible heat transfer

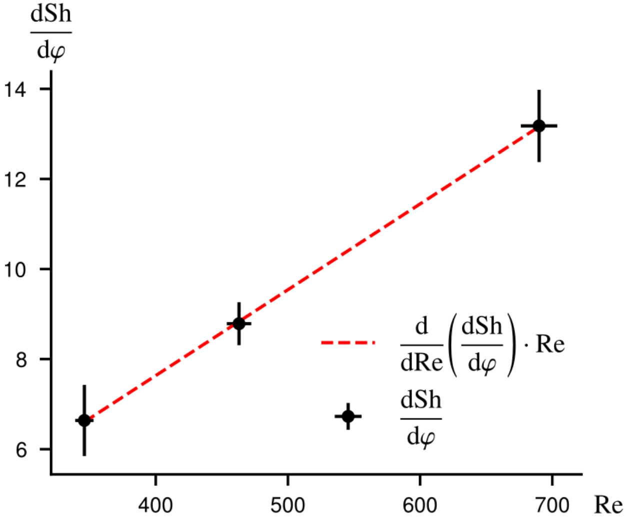


latent heat transfer condensation

$$\mathrm{Sh}_c(\varphi_{\mathrm{ein}}, \mathrm{Re}) = 0.34(7)\varphi_{\mathrm{ein}}^{4.31(10)}\mathrm{Re}^{0.62(4)}$$





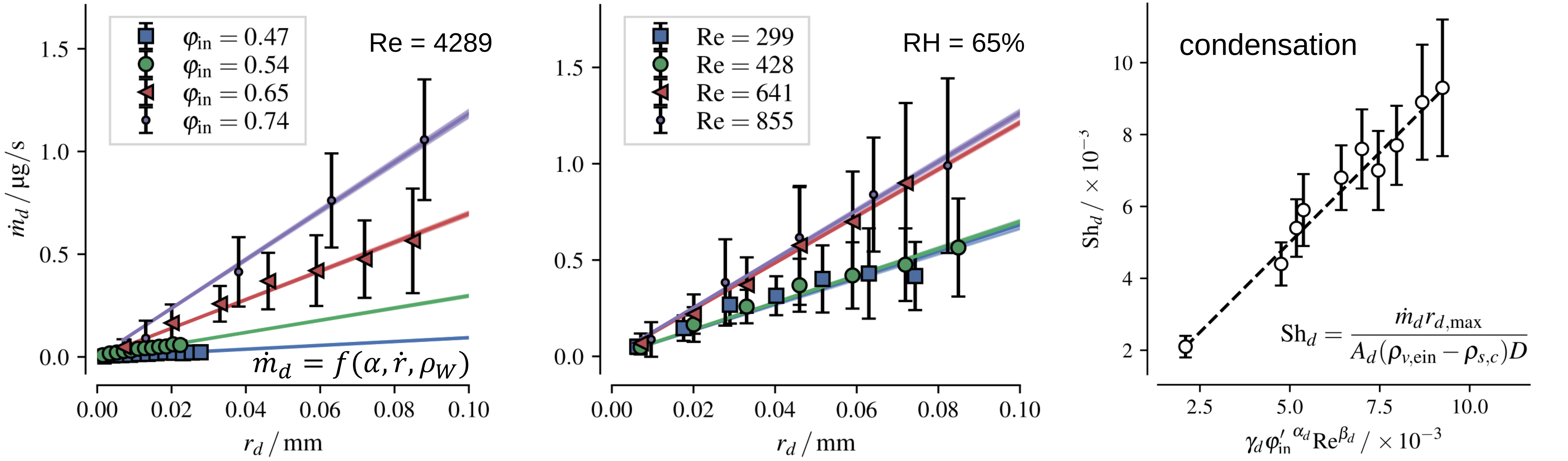


- sensible heat transfer scales with Re
- latent heat transfer scales with relative humidity and Re
- impact of humidity stronger than Re

- Sh scales linearly with relative humidity
- dSh/dφ scales linearly with Re

SCALING OF COVERAGE RATIO

SCALING OF LATENT HEAT TRANSFER AS A FUNCTION OF DROPLET RADIUS



$$\mathrm{Sh}_{d,e}(\mathrm{Re}, \varphi_{\text{ein}}) = 8.56(8) \times 10^{-4}\,\mathrm{Re}^{0.67(9)}\,\varphi_{\text{ein}}^{-0.68(7)}$$

- vapour mass transfer scales linear with droplet size
- higher mass transfer per area for larger droplets
- larger deviation of mass transfer with increasing droplet size
- two Re-regimes of mass transfer (laminar / turbulence or wall jet detachment on the cooled wall)
- Scaling of latent heat transfer (Sh) as a function of RH and Re

SUMMARY AND OUTLOOK

- Dropwise condensation depends on surface and local as well global flow conditions
- Large-scale flow structure formation of the forced flow determines the global heat transfer
    - Sensible heat transfer (Nu) scales linearly with Re
    - Latent heat transfer (Sh) scales linearly with Re and RH
- Local heat and mass transfer depends on Re, RH, droplet size and coverage ratio
    - coverage ratio scales linearly with Re and RH
    - the vapour mass transfer increases linearly with the droplet size
    - impact of large-scale flow on the local heat transfer (Re-regimes)
    - Latent heat transfer (Sh) scales with Re and RH

- Further investigation and analysis of the impact of thermal convective flows
- Statistical analysis of droplet size distribution dynamics
- Development of universal prediction models / models for numerical simulations
- Model for the coupling of machine learning methods and Reynolds-Averaged Navier-Stokes simulations for the prediction of droplet condensation and evaporation
- Impact of different modes of evaporation on the latent heat transfer

ANY QUESTIONS ?

Konstantin Alexander Niehaus
Experimentelle Untersuchung des Skalenverhaltens bei Kondensation und Verdampfen in einem generischen Fahrzeugscheinwerfer
PHD Thesis (2023)
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Marie-Christine Volk
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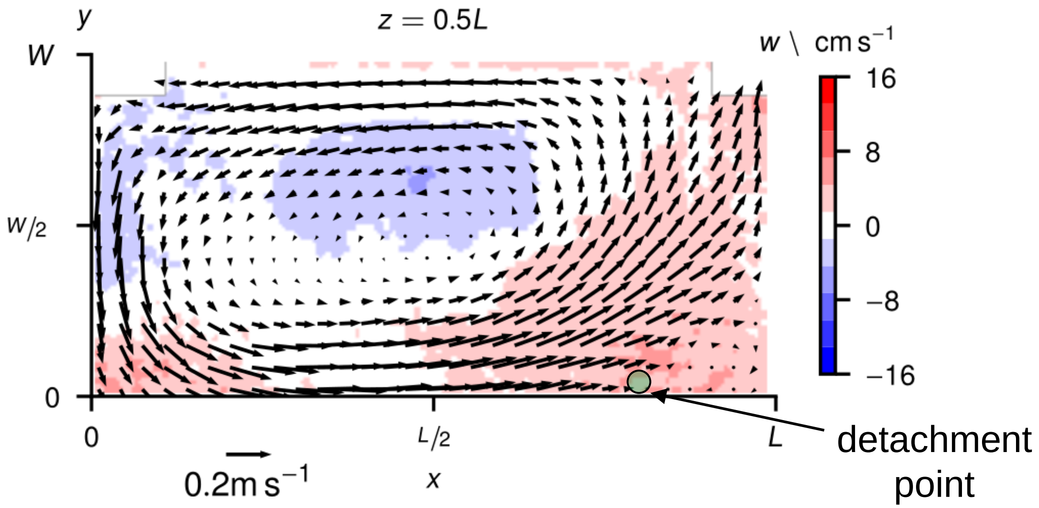
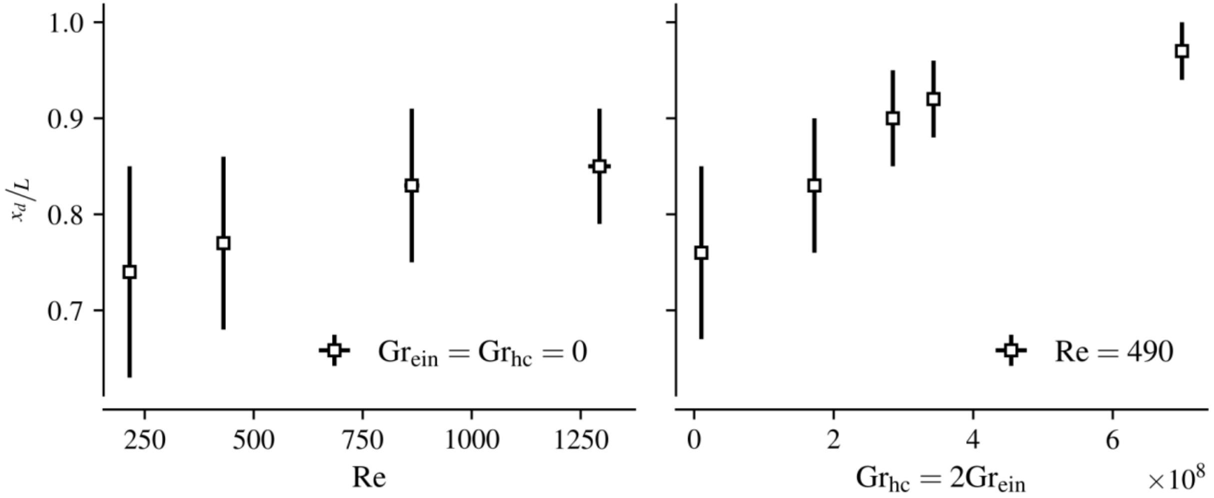
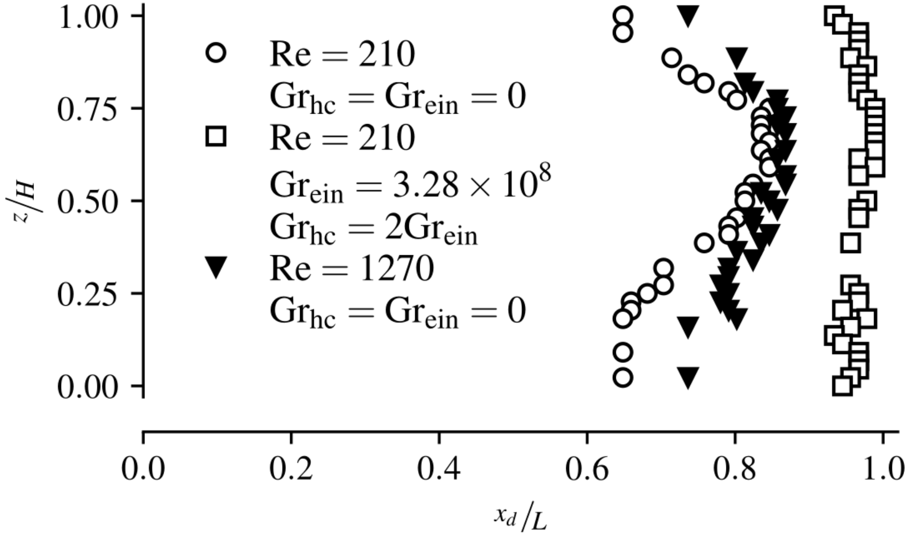
DLR Deutsches Zentrum für Luft- und Raumfahrt

COOLED WALL FLOW DETACHTMENT



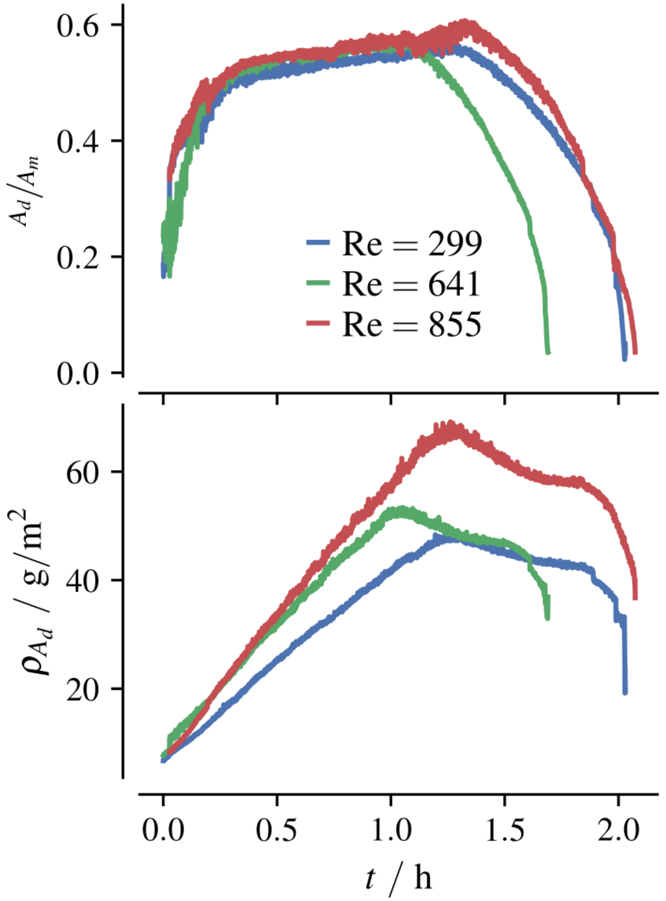


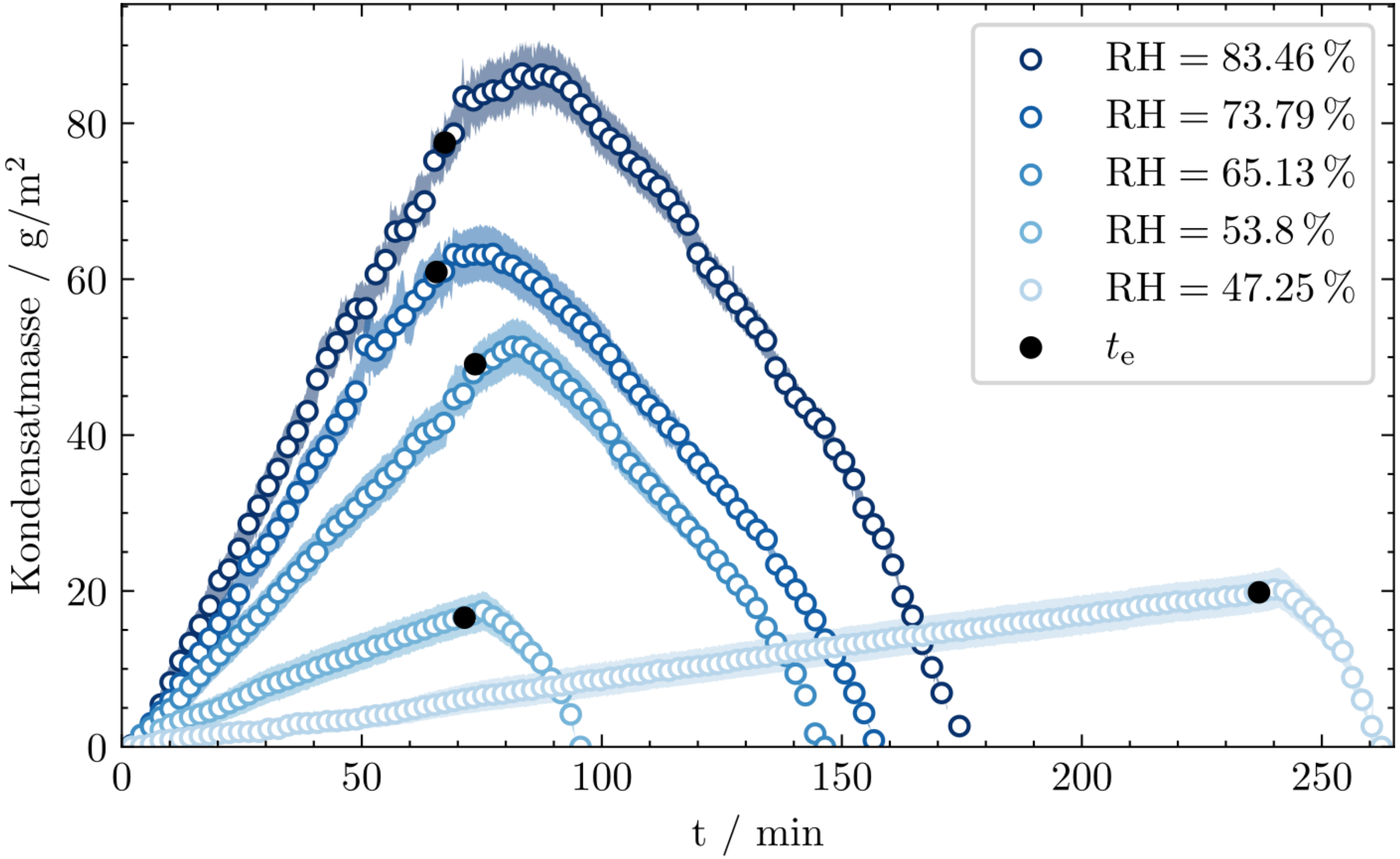


- line of detachment depends on Gr and Re
- thermal convective vertical flow leads to increasing turbulence near the isothermal walls → homogeneous distribution of the detachment point in vertical direction
- for pure forced convection (Gr = 0) detachment point later with increasing Re
- increasing Gr leads to later detachment
- decrease of fluctuations with increasing Gr → stabilisation of the detachment position in x-direction

detachment point scales with Re and Gr ≠ large-scale flow

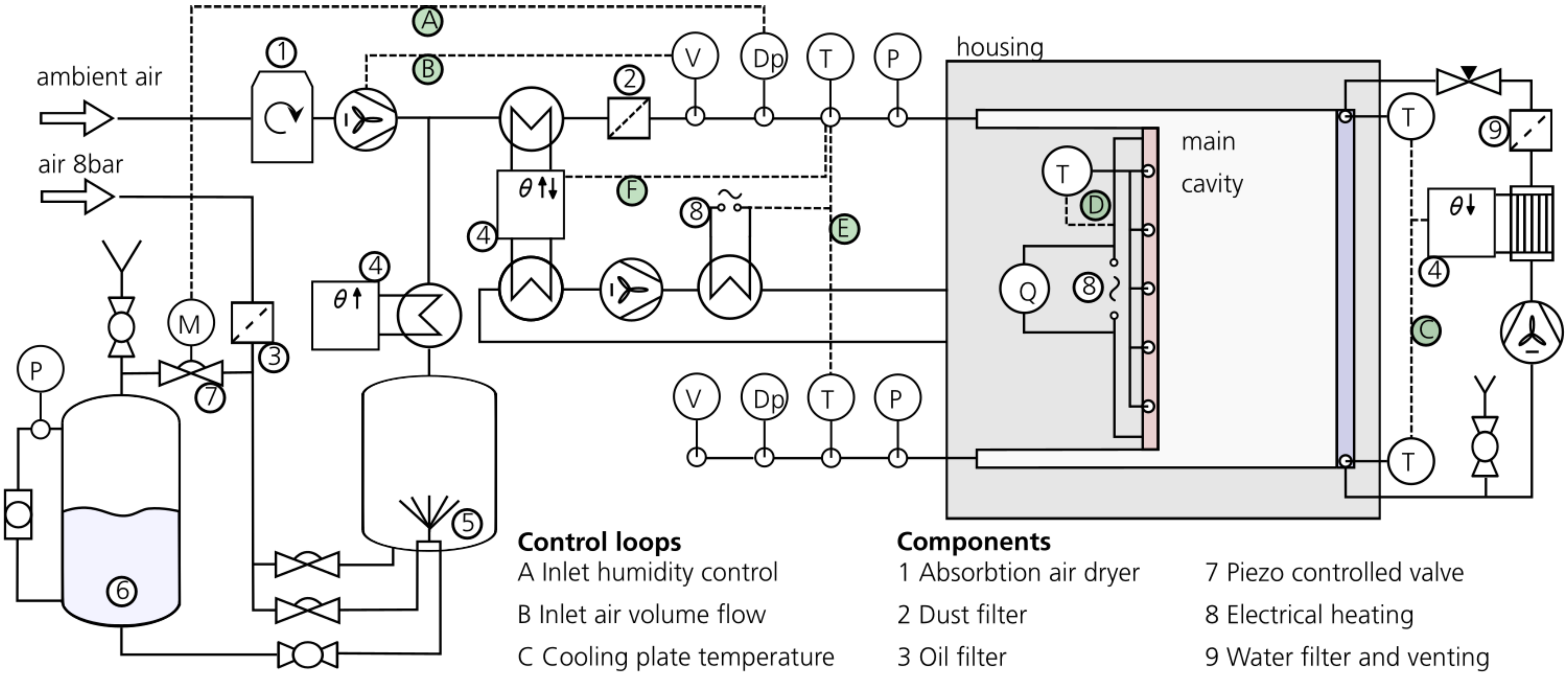
VAPOUR MASS TRANSFER AND SURFACE COVERAGE





- surface coverage is limited (~ 50% - 60%)
- linear vapour mass increase

MEASUREMENT CONTROL



Control loops
A Inlet humidity control
B Inlet air volume flow
C Cooling plate temperature
D Heating plate temperature
E Housing ambient temperature
F Inlet temperatur

Components
1 Absorbtion air dryer
2 Dust filter
3 Oil filter
4 Temperature control unit
5 Air atomizing nozzle
6 Purified water reservoir
7 Piezo controlled valve
8 Electrical heating
9 Water filter and venting