Referenzexperimente im mehrphasigen Windkanal, numerische Simulationen und Validierung

Dipl.-Ing. Róbert Bordás, Prof. Dr.-Ing. Dominique Thévenin

TH 881/13-1

Lehrstuhl für Strömungsmechanik und Strömungstechnik (LSS), Otto-von-Guericke-Universität Magdeburg

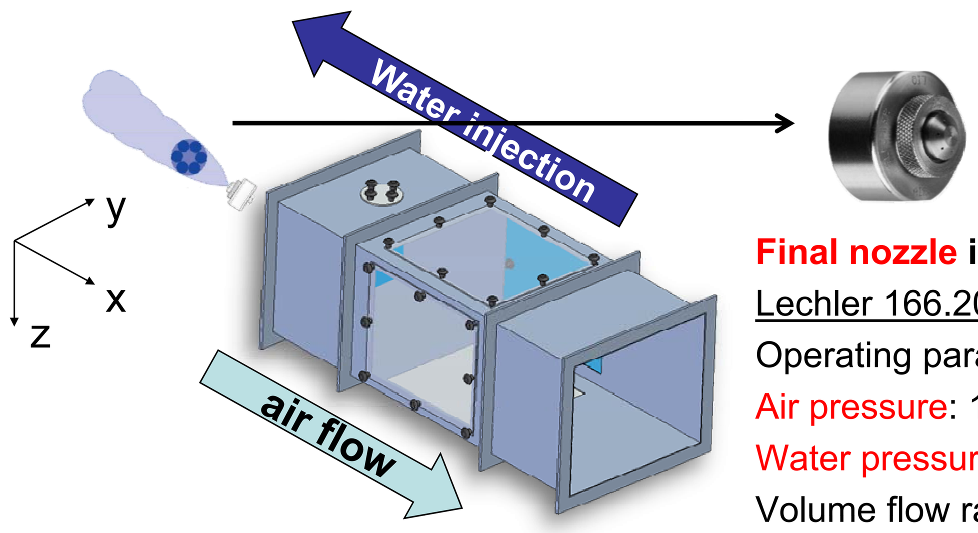
Modeling physical properties…

Cloud properties	modeled in wind tunnel
Saturated air	relative humidity > 95%
Vertical velocities ~ a few m/s	3 m/s air velocity
Liquid water content (LWC) ~ 0.1-1 g/m³	1 g/m³
Relatively small drop diameters	d_{mean} ~ 15 µm
Number density ~ several hundred/cm³	100-400/cm³

… and turbulence

Denomination	Formula	In clouds	In the wind tunnel
Max. size of structures:	L	$10^2 \dots 10^3$ m	0.55 m
Reynolds number:	$Re = \frac{v \cdot L}{\upsilon}$	$10^6 \dots 10^7$	$1.1 \cdot 10^5$
Turbulence length scale:	$l = 0.16\,Re^{-1/8}$	10^2 m	0.04 m
Turbulent kinetic energy:	$k = \frac{3}{2} u'^2$	~ 1 m²/s²	0.1 m²/s²
Dissipation rate:	$\varepsilon = c_\mu \frac{k^{3/2}}{l}$	~ 10^{-2} m²/s³	0.14 m²/s³
Kolmogorov length scale:	$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$	~ 10^{-3} m	$4 \cdot 10^{-4}$ m
Kolmogorov time scale:	$\tau_\eta = \left(\frac{\nu}{\varepsilon}\right)^{1/2}$	~ 10^{-2} s	10^{-2} s

Two-phase wind tunnel with water injection



Final nozzle identified: Lechler 166.208.16.12

Operating parameters:

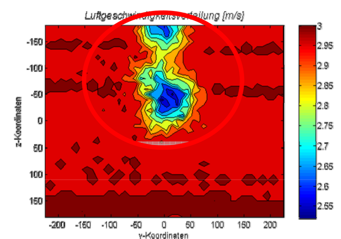
Air pressure: 1.2 bar

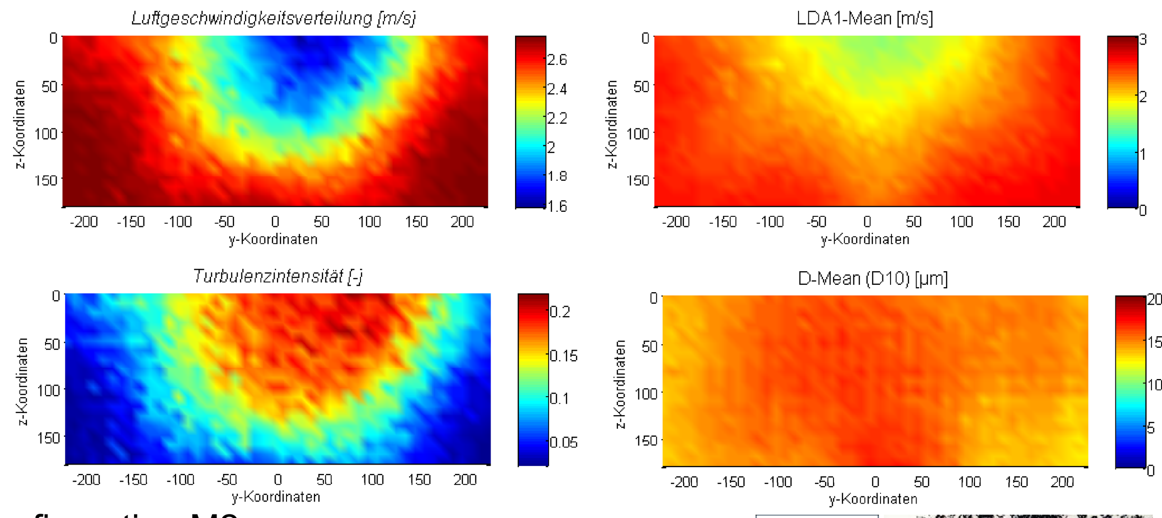
Water pressure : 0.9 bar

Volume flow rate: 0.1 l/min

Difficult requirements for the injection:

- •Small droplet diameters ⇒ Pressure atomizer
- •Broad spray ⇒ nozzle with 60° cone angle
- •Low droplet velocities, avoiding 6-hole pattern ⇒ injection in counter-flow direction
- •Flow disturbance induced by the nozzle connector ⇒ only the lower half of the test-section is used for experiments





Concentration / Collisions

Liquid volume fraction (φ =10^{-6}) is well within the **dilute** domain.

According to Abrahamson (1975) the collision rate can be defined as:

$$N_C = \frac{1}{2} C^2 d^2 \sqrt{\frac{16 \pi v_p^2}{3}}$$

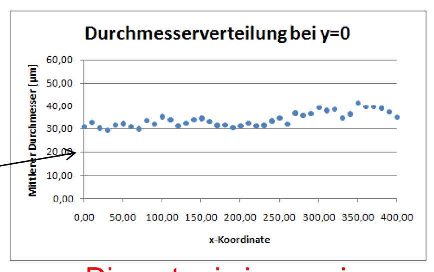
≈$2.8 \cdot 10^6$ collisions/s in the measurement section of the wind tunnel (0.45 m x 0.18m x 0.4m)

Average residence time in the measurement section: ~ 0.15 s

Average droplet amount in the measurement section: $7.8 \cdot 10^6$

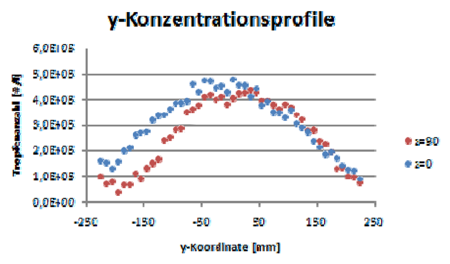
} ~5% collision probability

proof



Diameter is increasing with the x-coordinate

Shadowgraphy results can also be used for the concentration calculation besides PDA. Good agreement with the theoretical estimations ☺



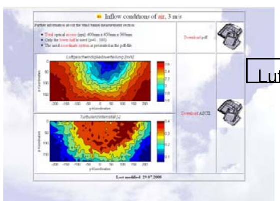
Configurations and working packages

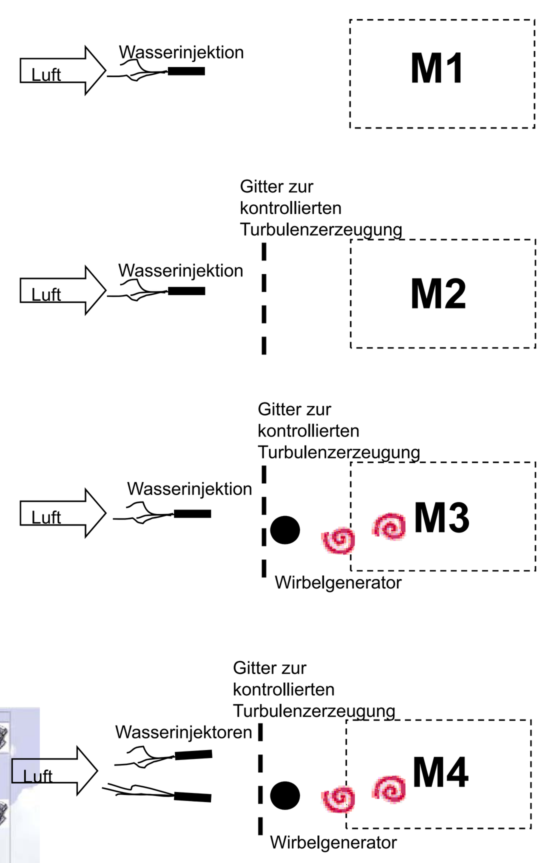
Method	Phase	Result	u'	Remarks
LDV	air	v (point)	+	1-C, high resolution
PDA	drops	v,d (point)	+	1-C, high resolution
PIV	air/drops	v	-	2-C, large meas. area
Shadowgraphy	drops	v,d	-	2-C, collisions
PTV	drops	trajectories	-	3-D, Lagrange

	M1	M2	M3	M4
LDV	✓	2008/IV	In process	2009/I
PDA	✓	2008/IV	In process	2009/I
PIV*	✓	2008/IV	✓	2009/II
Shadowgraphy	✓	-	-	2009/II

Results into the look-up-table for validation of companion numerical simulations:

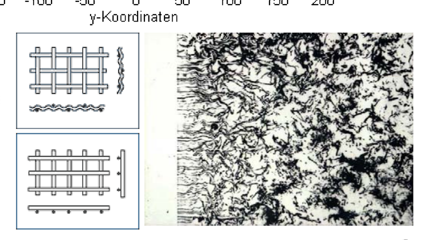
www.ovgu.de/isut/lss/metstroem



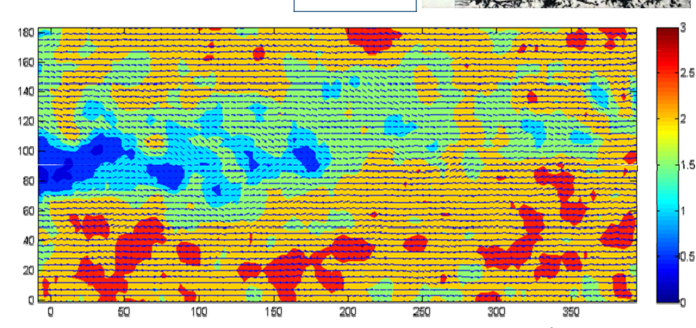


AP-E2 (finished):
Measuring the configuration M1
Results can be seen here and the data can be found in the look-up table

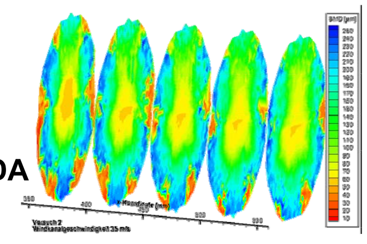
AP-E3 (in process): Measuring the configuration M2
The theoretical layout of an optimal grid is thoroughly examined. The main task is to create a homogeneous turbulence with suitable properties.



AP-E4 (first results):
Measuring the configuration M3
Vortex generation with the help of a cylinder. First results can be seen here. The final data will be transferred to the look-up table within the next weeks.



AP-E5 (2009):
Measuring the configuration M4
Experience with different nozzles available. A suitable nozzle pair has been identified and is available. The droplet spectra have been measured separately.



Reference experiments in a multiphase wind tunnel, numerical simulation and validation

Volker John, Ellen Schmeyer

FR 6.1 – Mathematik, Universität des Saarlandes, Postfach 15 11 50, 66041 Saarbrücken

Droplet size distribution

- model for ideally mixed fluid, Shaw (2003)

$$\begin{aligned}
&\partial_t f(t,r) \\
&= J(t,r) - \partial_r\big(g(t,r)f(t,r)\big) - \int_0^\infty \kappa(r,r')f(t,r)f(t,r')\,dr' \\
&+ \frac{1}{2}\int_0^r \left(1 - \frac{r'^3}{r^3}\right)^{-\frac{2}{3}} \kappa\left((r^3 - r'^3)^{\frac{1}{3}}, r'\right) f\left(t, (r^3 - r'^3)^{\frac{1}{3}}\right) f(t,r')\,dr'
\end{aligned}$$

- r – radius of droplets, internal coordinate
- $f(t,r)$ – droplet size distribution
- $J(t,r)$ – particle source term, nucleation rate
- $g(t,r)$ – growth rate; model for sufficiently large droplets and small supersaturations typically given in the atmosphere: $g(t,r) = \gamma s/r$
- γ – function of environment, like temperature
- s – supersaturation

- equation is conservation law

change of droplet size distribution
= (nucleation + growth + collision + coalescence) of droplets

- goals in the first period:
  - couple droplet size distribution to flow field
  - consider nucleation and growth of droplets
- model system in the first period (dimensionless):
  - Navier–Stokes equations

$$\begin{aligned}
\partial_t \mathbf{u} - 2\nabla \cdot (Re^{-1}\mathbb{D}(\mathbf{u})) + (\mathbf{u}\cdot\nabla)\mathbf{u} + \nabla p &= \mathbf{0} \quad \text{in } (0,T] \times \Omega, \\
\nabla \cdot \mathbf{u} &= 0 \quad \text{in } [0,T] \times \Omega,
\end{aligned}$$

  - transport equation for droplet size distribution

$$\partial_t f(t,\mathbf{x},r) = J(t,\mathbf{x},r) - \partial_r\big(g(t,r)f(t,\mathbf{x},r)\big) - \mathbf{u}\cdot\nabla_{\mathbf{x}} f(t,\mathbf{x},r)$$

in $(0,T) \times \Omega \times (r_{\min}, r_{\max})$

- Ω – wind tunnel

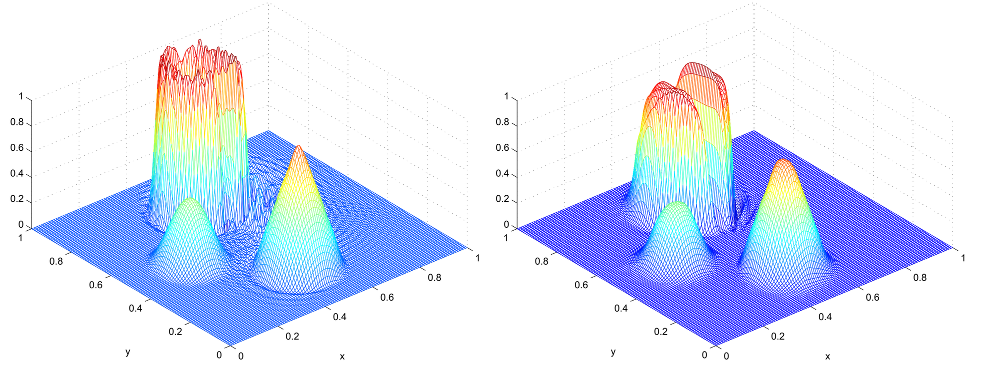
Numerical simulation of convection–dominated equations with finite element methods

- model problem of transport equation for droplet size distribution: scalar convection–diffusion–reaction equations

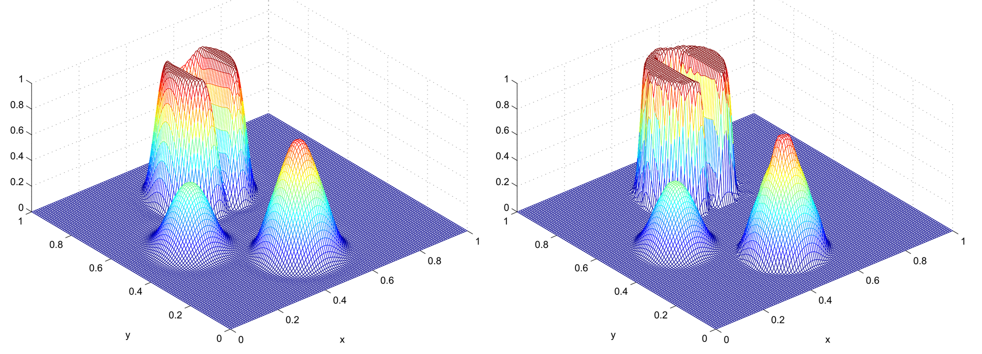
$$\frac{\partial u}{\partial t} - \varepsilon\Delta u + \mathbf{b}\cdot\nabla u + cu = 0 \quad \text{in } (0,T] \times \Omega$$

ε – diffusion, $\mathbf{b}$ – convection, $\|\mathbf{b}\| \gg \varepsilon$, c – reaction

- studied finite element methods:
  - Streamline–Upwind Petrov–Galerkin (SUPG) FEM (standard method); Hughes, Brooks (1979)
  - Spurious Oscillations at Layers Diminishing (SOLD) methods; J., Knobloch (2007,2008)
  - Finite Element Methods with Flux Corrected Transport (FEM–FCT); Kuzmin, Möller (2005), Kuzmin (2008)
  - Local Projection Stabilization (LPS) scheme; Matthies, Tobiska, Skrzypacz (2007)
- Rotating body problem in 2D
  - SUPG (left), SOLD method from Knopp, Lube, Rapin (2006) with $C = 0.5$ (right)



  - linear (left) and nonlinear FEM–FCT (right)

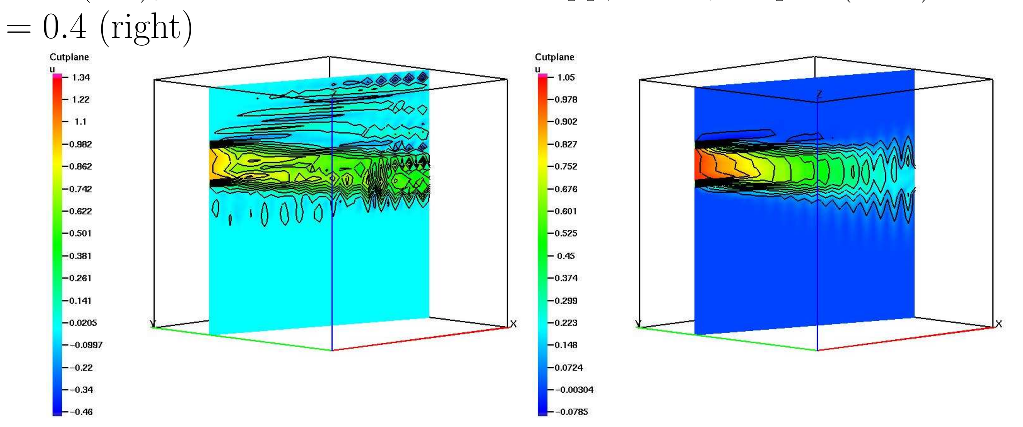


  - variation of finite element solutions (optimal value = 1) and computing times in seconds

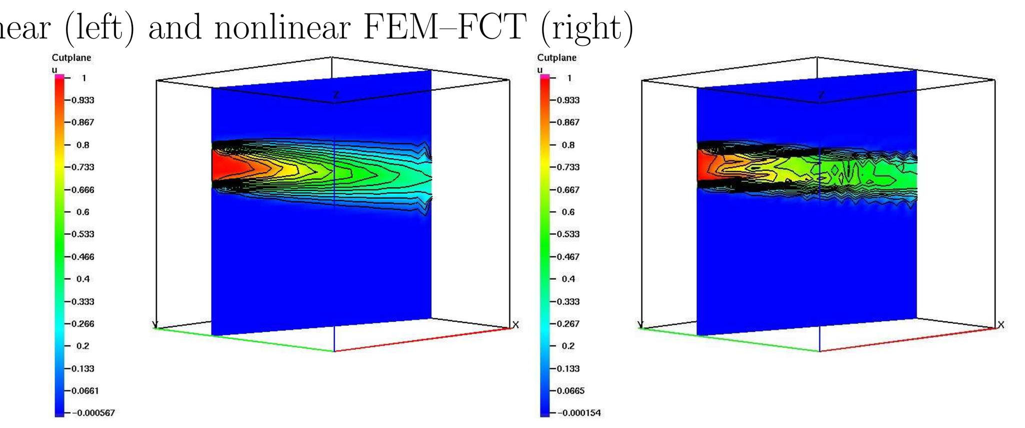
method	variation	time
SUPG	1.5567	2618
SOLD, $C = 0.1$	1.3990	9501
SOLD, $C = 0.5$	1.2546	22846
SOLD, $C = 1.0$	1.1289	50693
FEM–FCT linear	1.0076	2613
FEM–FCT nonlinear	1.0013	47939

  - reference: J., S., Comp. Meth. Appl. Mech. Engrg. (2008), 198, 475 - 494, 2008

- Transport through a domain in 3D
  - SUPG (left), SOLD method from Knopp, Lube, Rapin (2006) with $C = 0.4$ (right)



  - linear (left) and nonlinear FEM–FCT (right)



  - computing times in seconds

method	Q_1	P_1
SUPG	5989	9473
SOLD, $C = 0.4$	33688	30932
FEM–FCT linear	5920	6509
FEM–FCT nonlinear	9768	10398

  - reference: J., S., Proceedings of BAIL 2008, in press
- conclusion: linear FEM–FCT methods performed best with respect to accuracy and efficiency

Coupling to turbulent flow simulation

- turbulent flow simulation: variational multiscale method; J., Kaya (2005)
- wind tunnel: $(0, 0.5) \times (0, 0.45) \times (0, 0.18)$, using symmetry in z–direction
- inflow: interpolation of measured mean velocity + random noise
- coupling of the equations: work in progress

Goals for the second period

- including collision and coalescence of droplets
- comparison with experimental data