



OTTO VON GUERICKE
UNIVERSITÄT
MAGDEBURG

VST

FAKULTÄT FÜR VERFAHRENS-
UND SYSTEMTECHNIK

DFG Deutsche
Forschungsgemeinschaft

MetStröm

Experimental investigation of two-phase flows representing cumulus cloud conditions

R. Bordás, E. Schmeyer, V. John and D. Thévenin

MetStröm Conference, 06/07/2011

Contents



- Motivation
- Experiments
 - Setup
 - Methods
 - Results
- Online database
- Experiments ⇔ simulations
- Conclusions

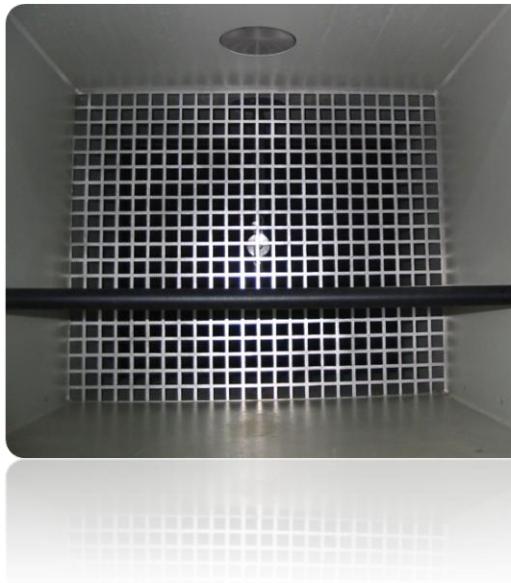
Contents

- Motivation



• Experiments

- Setup
- Methods
- Results



- Online database

- Experiments ⇔ simulations

- Conclusions



Contents

- Motivation



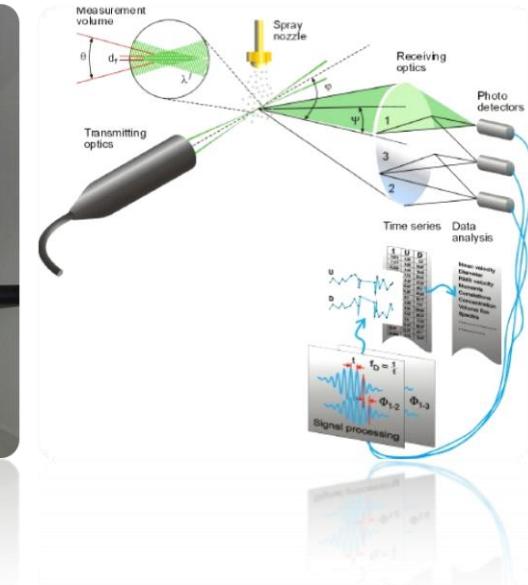
• Experiments

- Setup
- Methods
- Results

• Online database

• Experiments \Leftrightarrow simulations

• Conclusions





Contents

- Motivation



• Experiments

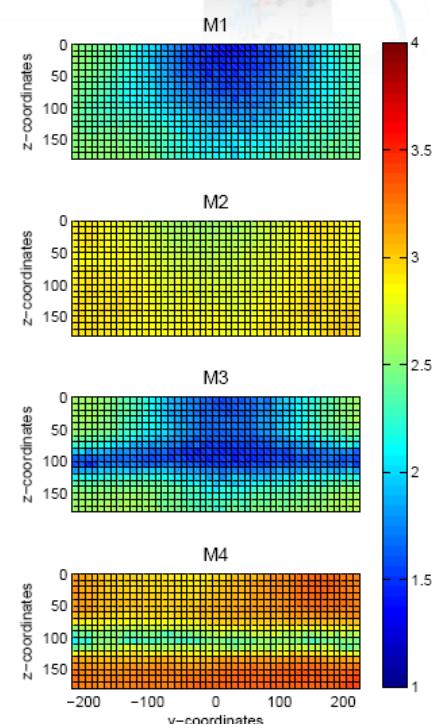
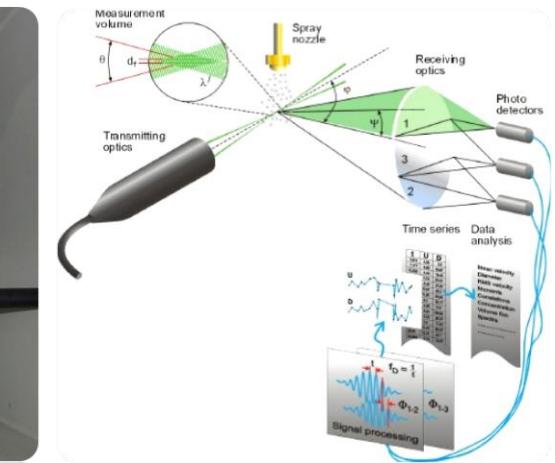
- Setup
- Methods
- Results



- Online database

- Experiments \leftrightarrow simulations

- Conclusions





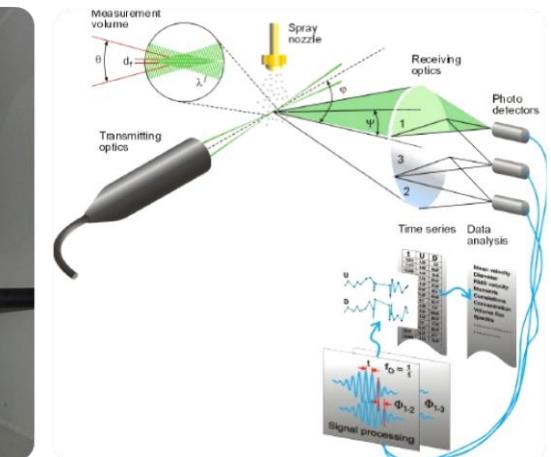
Contents

- Motivation



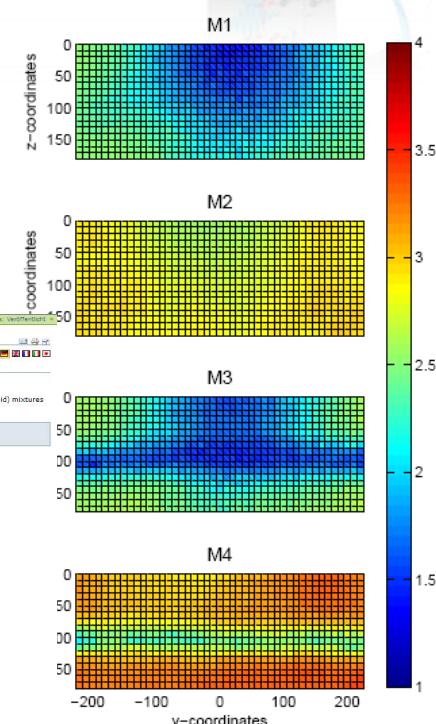
- Experiments

- Setup
- Methods
- Results



- Online database

- Experiments \leftrightarrow simulations



- Conclusions



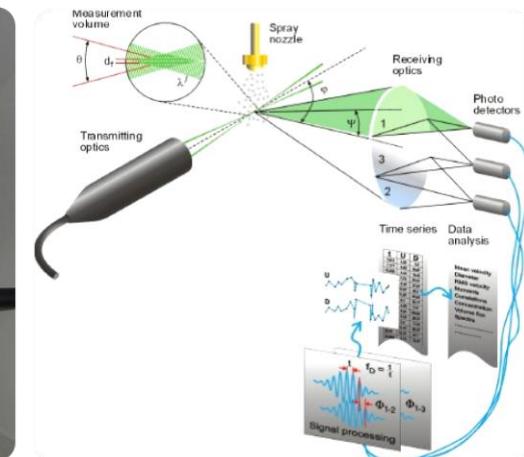
Contents

- Motivation

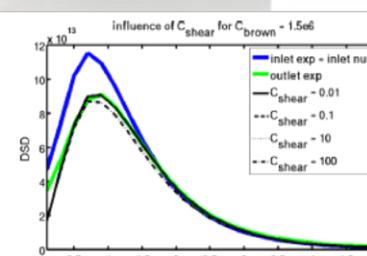
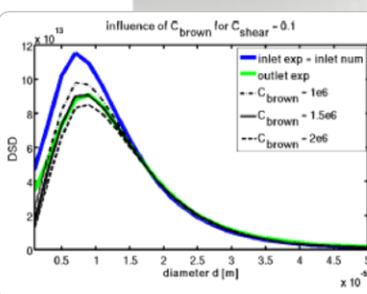


- Experiments

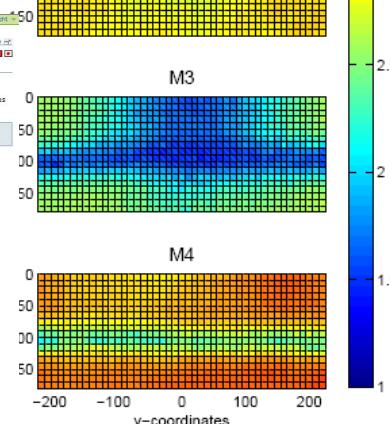
- Setup
- Methods
- Results



- Online database



- Experiments \leftrightarrow simulations



- Conclusions



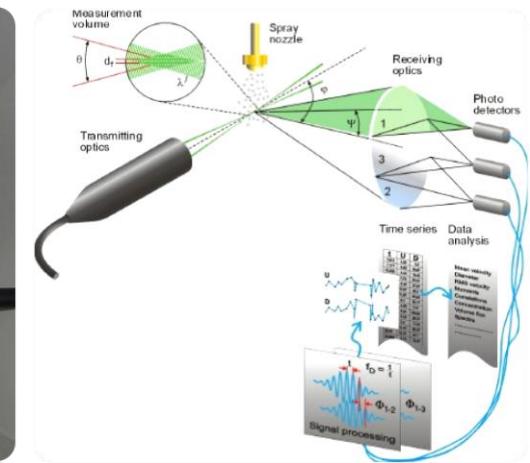
Contents

- Motivation

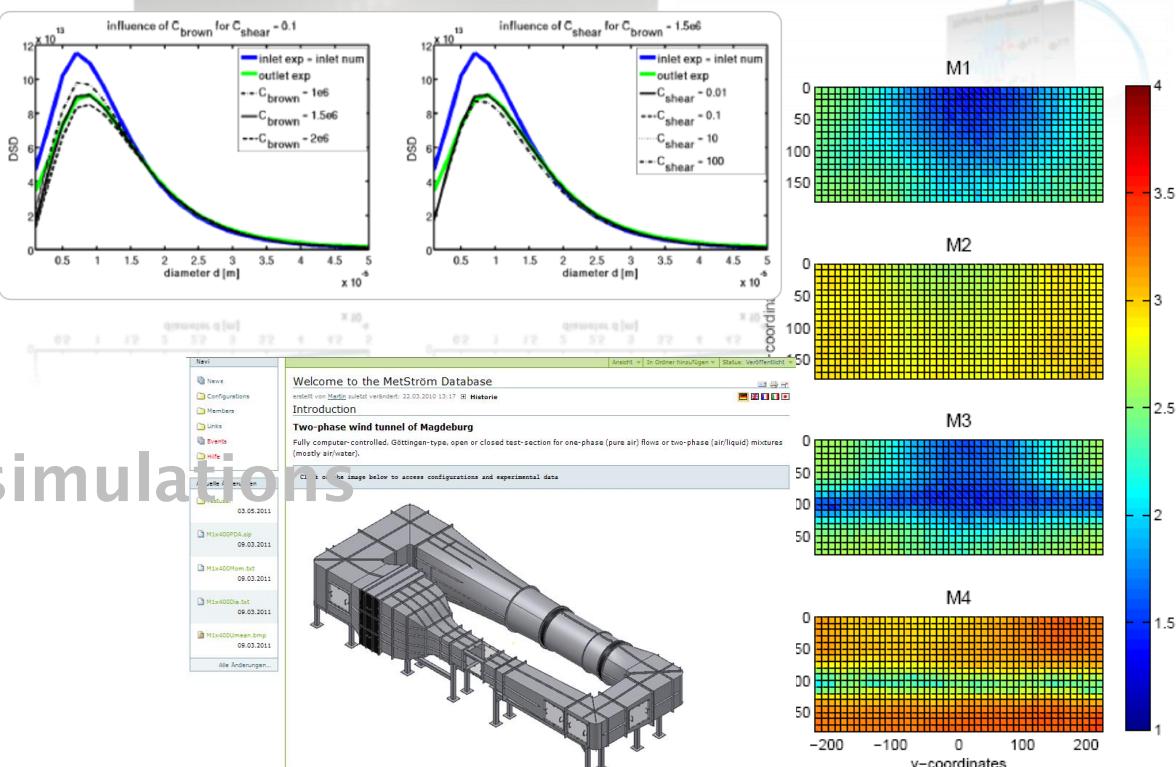


- Experiments

- Setup
- Methods
- Results



- Online database



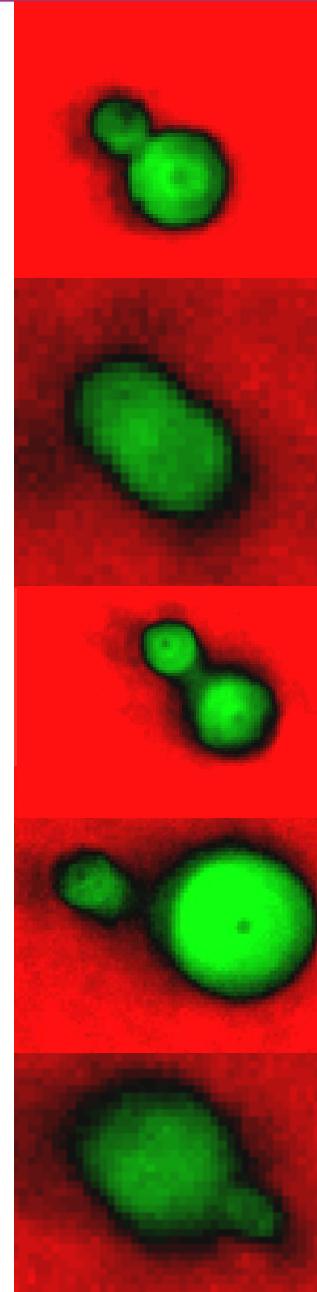
- Experiments \leftrightarrow simulations

- Conclusions



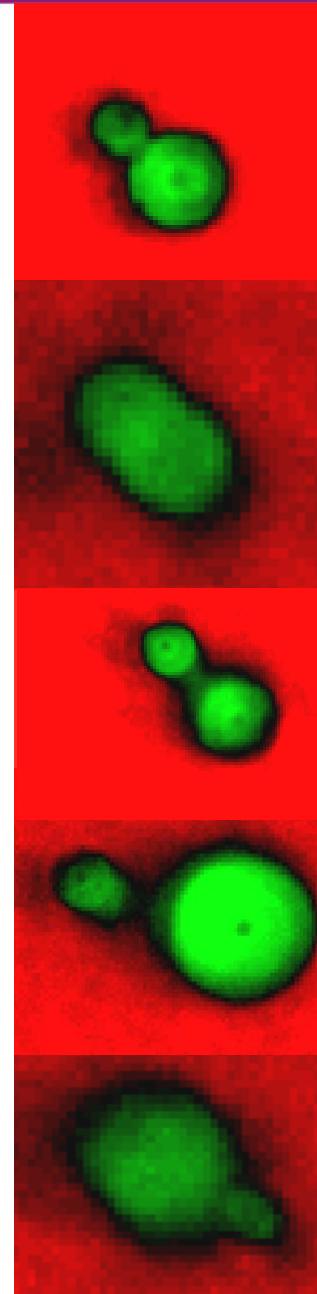
Motivation

- Poor reliability of **precipitation forecasting**
 - In particular **warm rain initiation** is a mystery
- Collision-induced growth in turbulent flows
 - Theory \Leftrightarrow observations: a factor of 2 or more

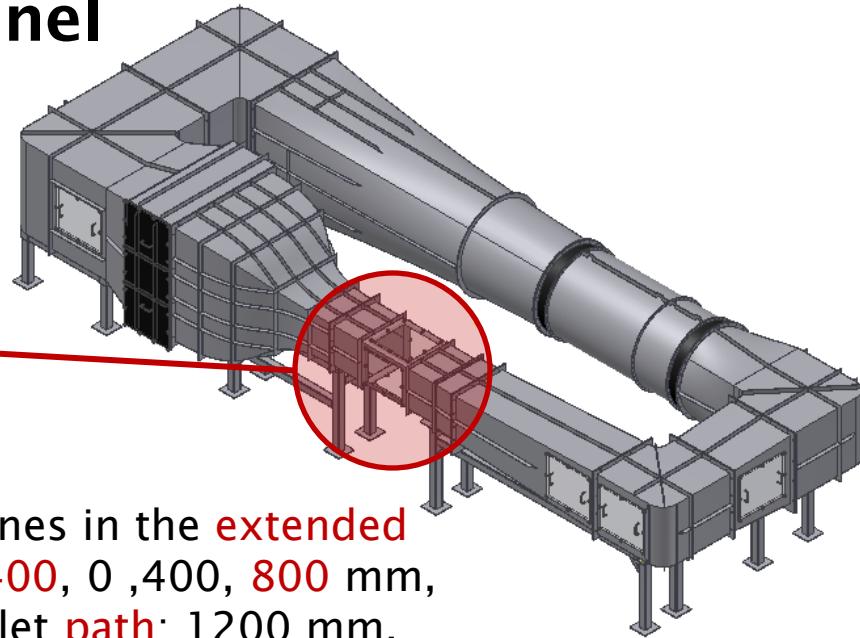
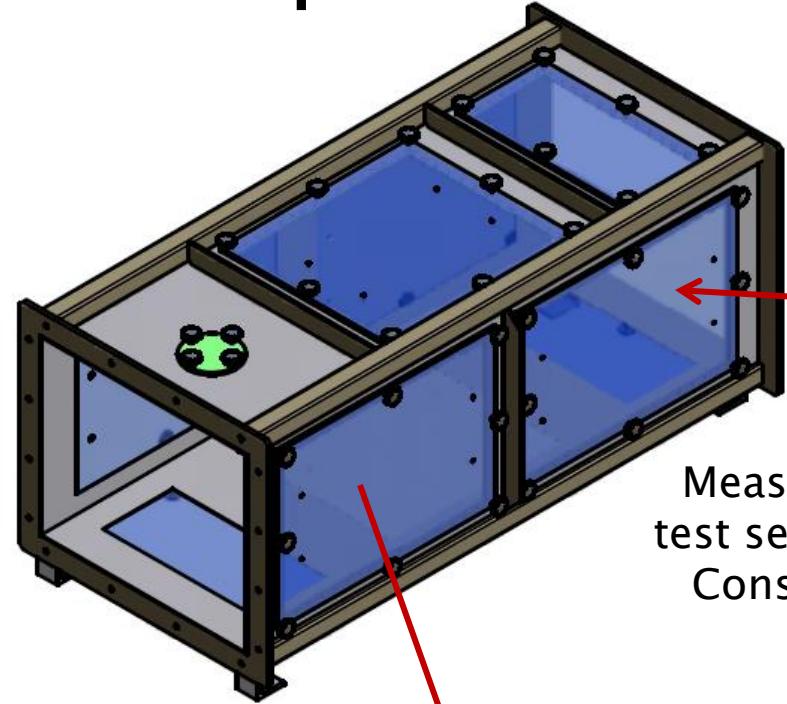


Motivation

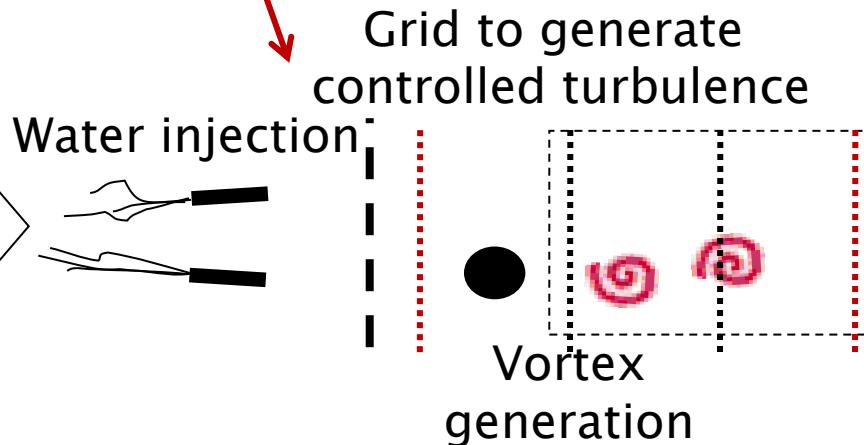
- Poor reliability of **precipitation forecasting**
 - In particular **warm rain initiation** is a mystery
 - Collision-induced growth in turbulent flows
 - Theory \Leftrightarrow observations: a factor of 2 or more
- ↓
- Experiments in wind tunnels are essential
 - Non-intrusive measurements
 - Experimental **characterization** of both phases
 - Droplet-droplet **interactions**
 - Freely available **database**
 - Quantifications of droplet **collision rates**
 - **Comparison** with theoretical predictions



Two-phase flow in wind tunnel

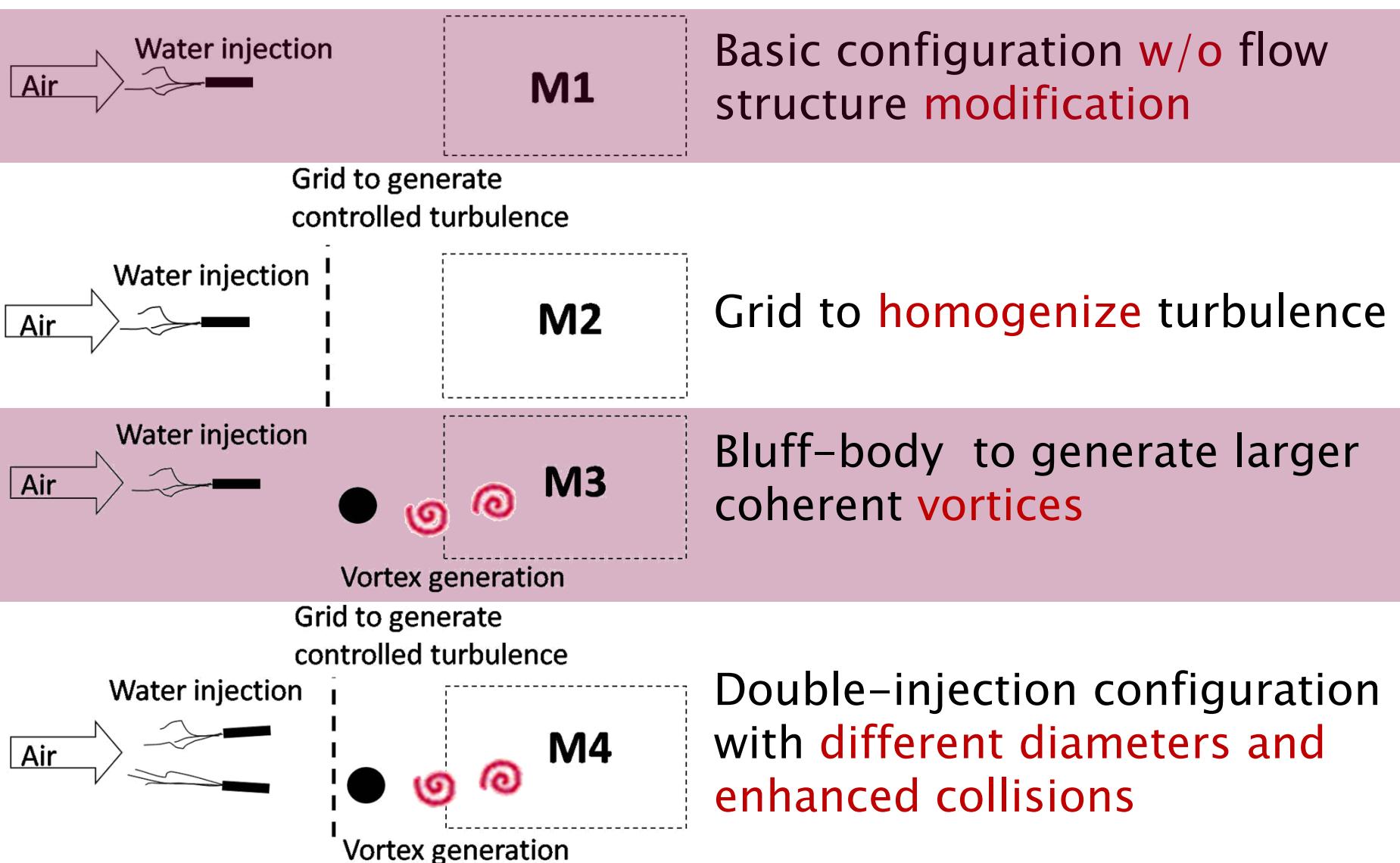


Measurement planes in the **extended** test section: $x = -400, 0, 400, 800$ mm,
Considered droplet **path**: 1200 mm,
Observation **time**: ~ 0.5 s

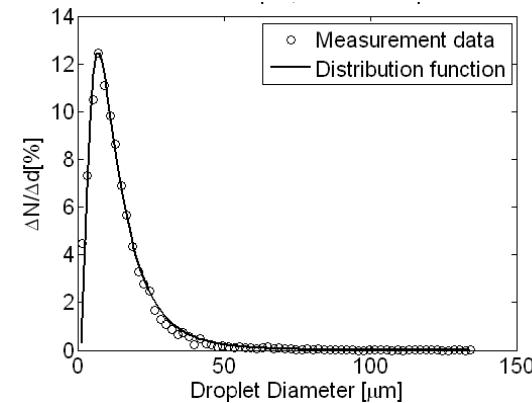
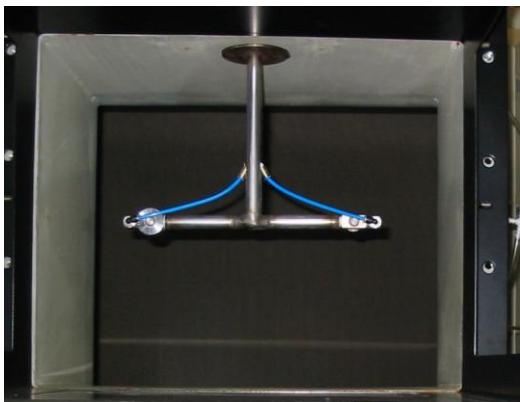


	clouds	wind tunnel
Humidity	Saturated	Saturated
U [m/s]	~ a few m/s	~ 2.5...3.0
LWC [g/m ³]	~ 0.1–3.5	~ 2
d_{10} [μm]	10–20	8.5...12.5
n [#/ cm^3]	up to 7000	~ 2000

Configurations M1-M4



Droplet injection



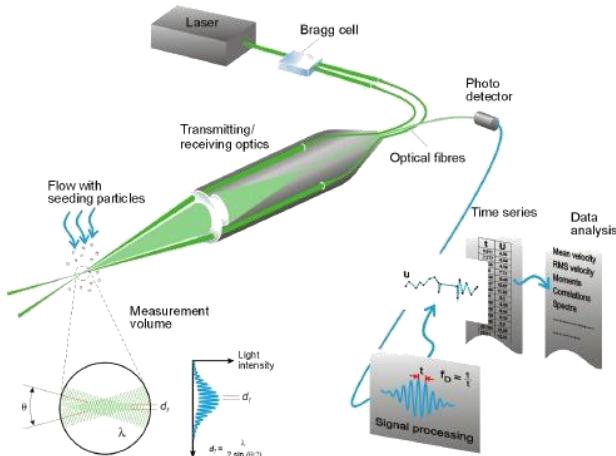
- Counter-flow direction
- Droplet distribution, measured by means of PDA
- Lognormal probability density function (PDF)

$$y = f(x|\mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{\frac{(-\ln(x)-\mu)^2}{2\sigma^2}}$$

- Since narrow distribution, characteristic diameters are applicable:
 - Mean diameter $d_{10} = 13.46 \mu\text{m}$
 - Volume mean diameter $d_{30} = 23.83 \mu\text{m}$

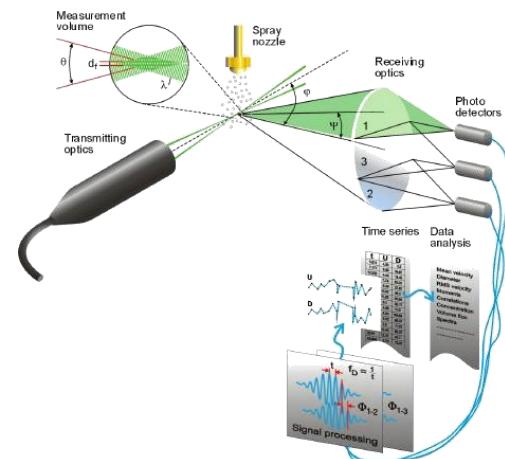
Experimental methods

Measurement method	Measured phase	Measured quantity	Derived quantity
LDV	air	u, u'	Tu, TKE
PDA	drops	u, u', d	DSD, n_d, u_{rel}
PIV	air and drops	u, v, w	$\varepsilon \rightarrow \eta, \tau_k$
Shadowgraphy	drops	u, w, d	collisions



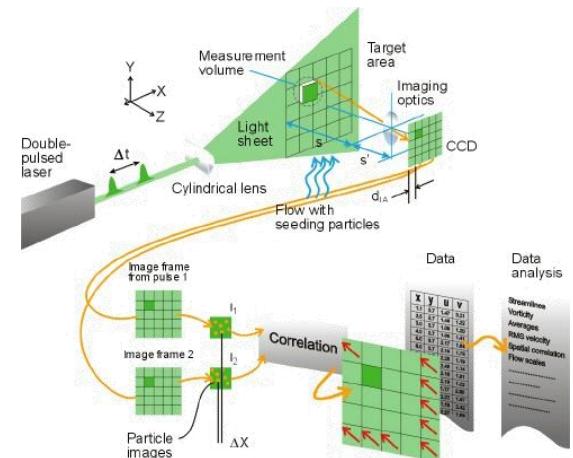
Experimental methods

Measurement method	Measured phase	Measured quantity	Derived quantity
LDV	air	u, u'	Tu, TKE
PDA	drops	u, u', d	DSD, n_d, u_{rel}
PIV	air and drops	u, v, w	$\varepsilon \rightarrow \eta, \tau_k$
Shadowgraphy	drops	u, w, d	collisions



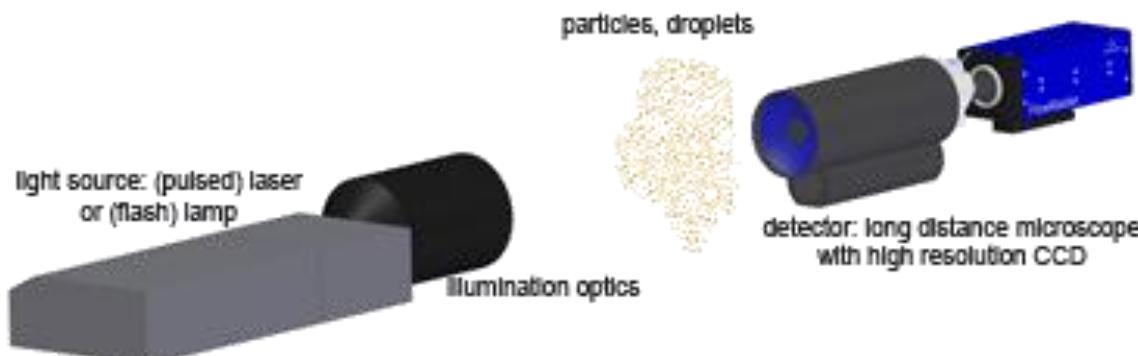
Experimental methods

Measurement method	Measured phase	Measured quantity	Derived quantity
LDV	air	u, u'	Tu, TKE
PDA	drops	u, u', d	DSD, n_d, u_{rel}
PIV	air and drops	u, v, w	$\varepsilon \rightarrow \eta, \tau_k$
Shadowgraphy	drops	u, w, d	collisions



Experimental methods

Measurement method	Measured phase	Measured quantity	Derived quantity
LDV	air	u, u'	Tu, TKE
PDA	drops	u, u', d	DSD, n_d, u_{rel}
PIV	air and drops	u, v, w	$\varepsilon \rightarrow \eta, \tau_k$
Shadowgraphy	drops	u, w, d	collisions

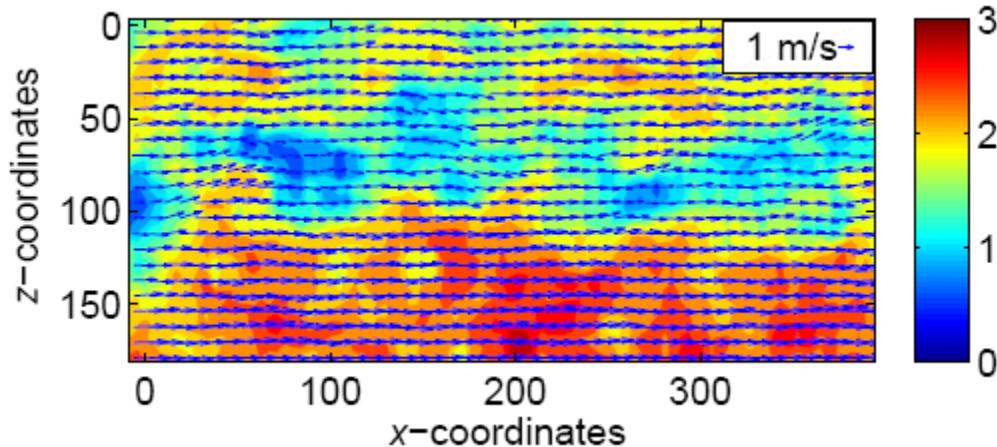


PIV measurements

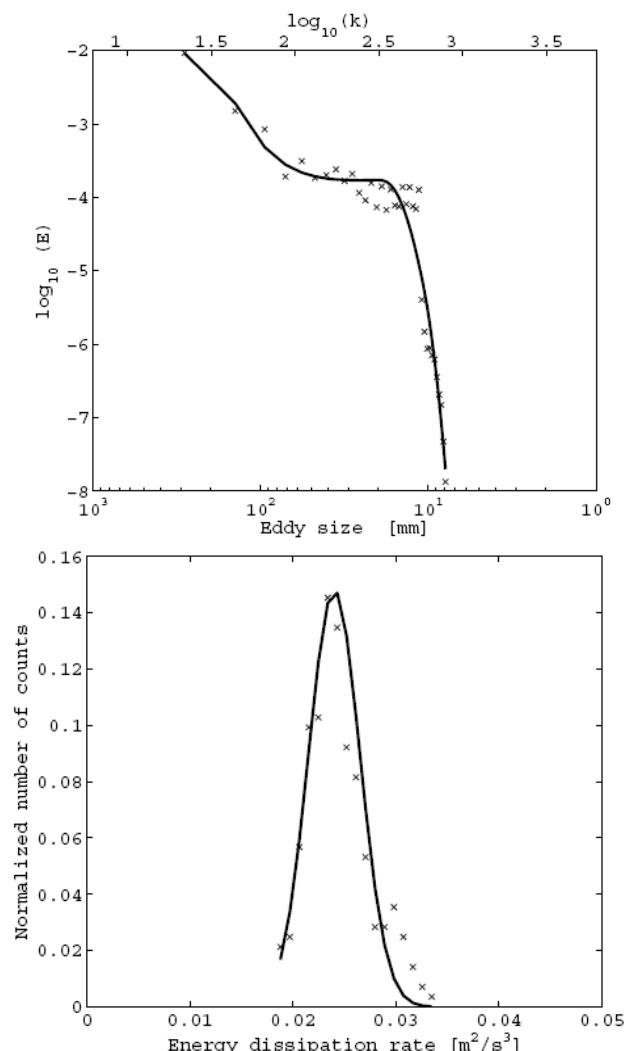
Velocity information at $y=0$, applied for the calculation of

- turbulent energy spectrum and
- dissipation rate

E.g., for configuration M3:



$$\varepsilon = \nu \frac{\partial v}{\partial x} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)$$



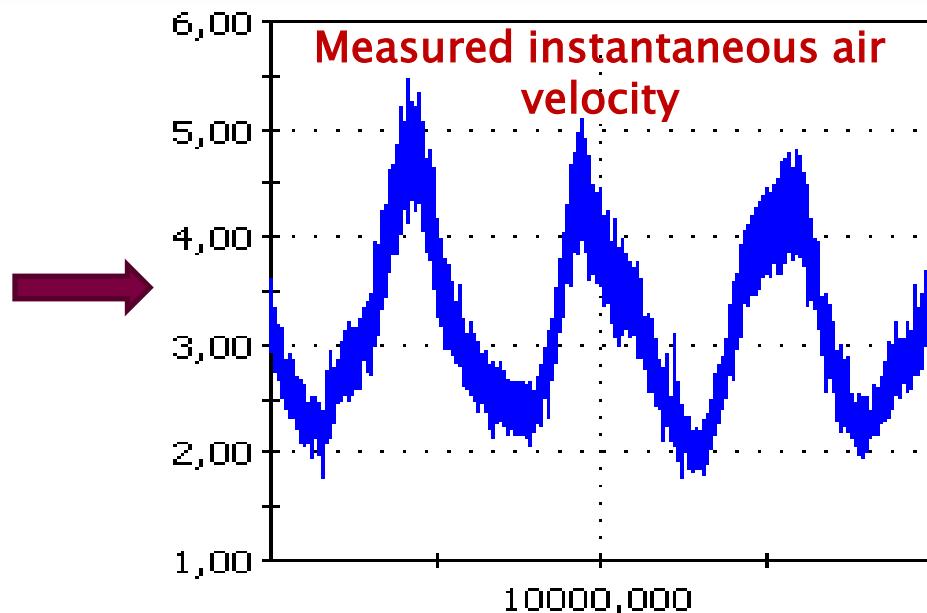
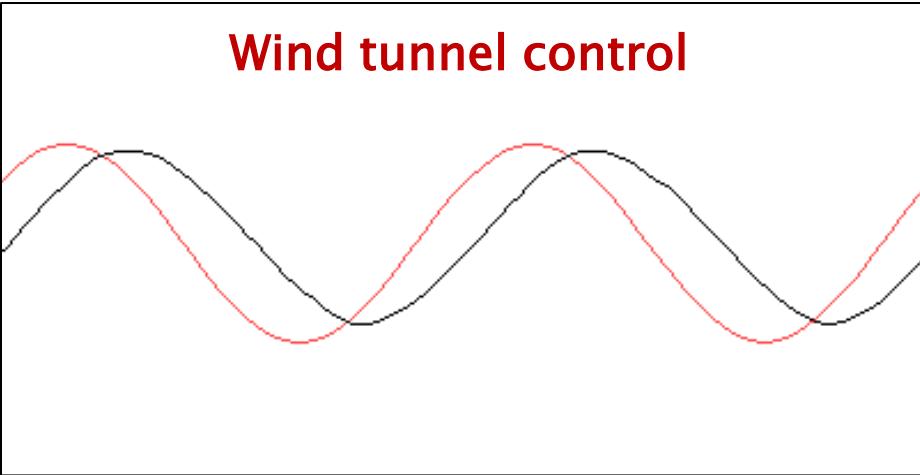


Measured mean values of different configurations

	M1	M2 (grid)	M3 (cyl.)	M4	Cumulus clouds
$U[\text{m/s}]$	2.45	2.93	2.32	2.92	1...8
$u' [\text{m/s}]$	0.25	0.18	0.33	0.35	0.8
$k [\text{m}^2/\text{s}^2]$	0.11	0.05	0.18	0.22	1
$d_{10} [\mu\text{m}]$	12.61	11.68	12.44	8.6	10...20
$\varepsilon [\text{m}^2/\text{s}^3]$	0.025	0.012	0.026	0.055	0.001...0.1
$\tau_k [\text{s}]$	2.5e-2	3.5e-2	2.4e-2	1.7e-2	1e-2
$\eta [m]$	6.2e-4	7.4e-4	6.1e-4	5.1e-4	1e-3
λ_g	1.1e-2	5.6e-3	4.9e-3	9.3e-3	1e-1
Re_λ	170	70	60	200	1e+5

Pulsating flow

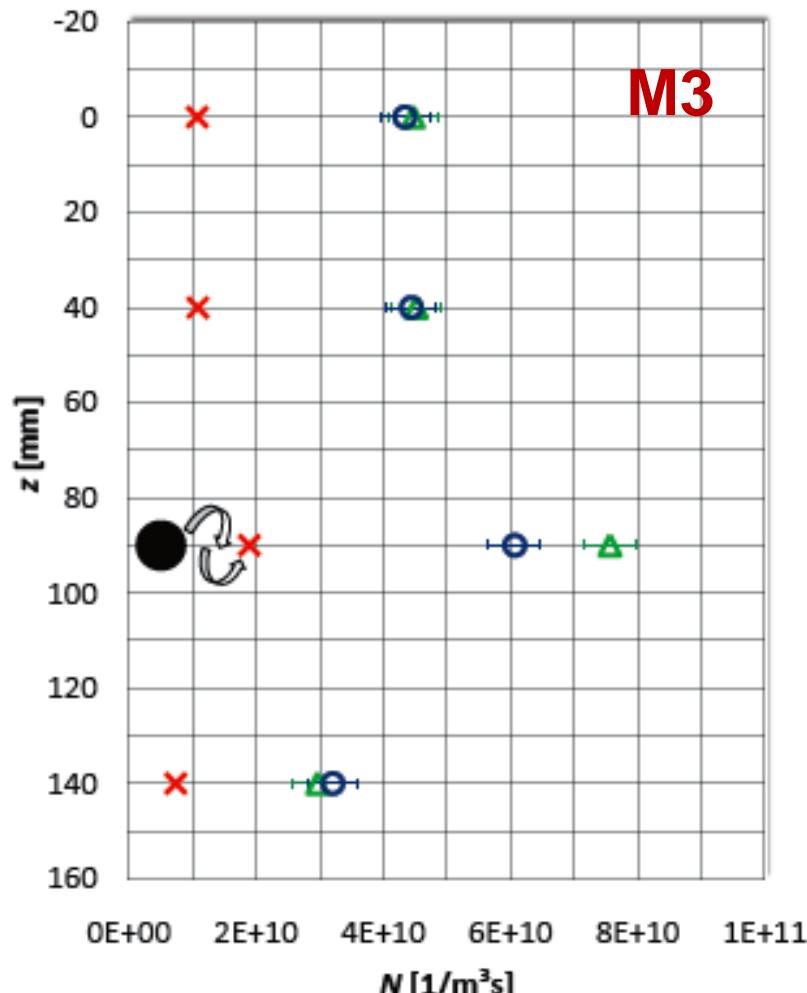
Wind tunnel control



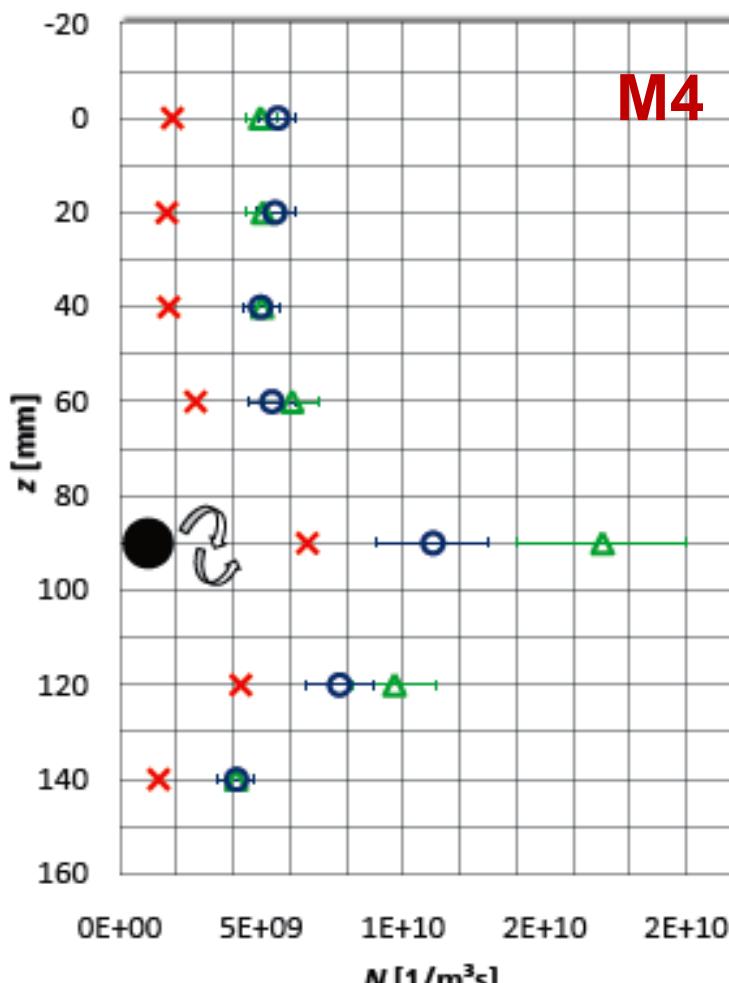
Property	Cumulus clouds	Measured or derived by	Conf. M4 (x=0)	Pulsating flow (x=0)
U [m/s]	0...6	LDV	2.92	3.02
Re	$10^6 \dots 10^7$	LDV	10^5	$1.1 \cdot 10^5$
u' [m/s]	0.8	LDV	0.35	0.84
k [m^2/s^2]	1	LDV	0.22	1.06
d_{10} [μm]	10...20	PDA	8.5	9.2

Shadowgraphy – collision rate: experiments vs. theory

- ▲ Experiments (n with standard deviation)
- Experiments (D with standard deviation)
- ✖ Theoretical approach (Williams and Crane)
- Position of bluff body



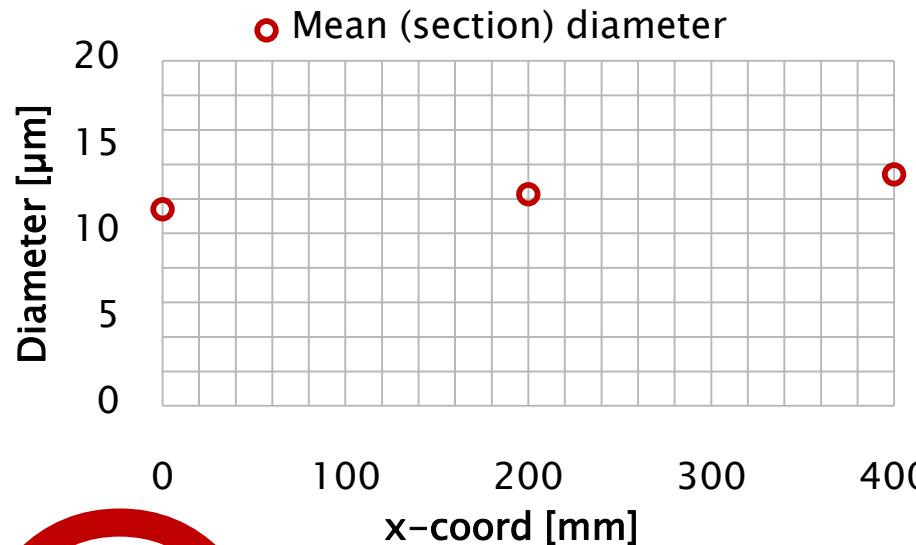
- ▲ Experiments (n with standard deviation)
- Experiments (D with standard deviation)
- ✖ Theoretical approach (Williams and Crane)
- Position of bluff body



*Williams, J.J.E. and Crane, R.I. Particle collision rate in turbulent flow. *Int. J. Multiphase Flow*, 1983. 9: p. 421.

Comparison (PDA \leftrightarrow Shadowgraphy)

- Are the experimental results realistic?
- Growth rate measured by PDA \leftrightarrow growth by droplet collision



The measured 0.05%
is considered here

Property	Value
Increase in d [%]	17.80
Increase in $V(\text{PDA})$ [%]	63.45
Residence time [s]	0.16
Collisions [1/ cm^3]	3810
Concentration [1/ cm^3]	5740
Increase in $V(\text{Sha.})$ [%]	66.37





Online database – www.ovgu.de/isut/lss/metstroem

MetStröm

look-up table

Website-Übersicht Barrierefreiheit Kontakt

Suche

Startseite News MetStröm Members Links

Anmelden Registrieren

Sie sind hier: Startseite

Navi

- News
- MetStröm
- Members
- Links

Introduction

Welcome to the MetStröm Database

erstellt von Martin zuletzt verändert: 17.04.2009 02:26

Further information about the wind tunnel and test section is coming soon, in case of any questions please contact me under the e-mail address on the top right. Please click the link or the photo to enter the MetStröm Portal.

MetStröm

April 2009

So	Mo	Di	Mi	Do	Fr	Sa
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30		

Nachrichten

Configuration M1 and M3 completed!! 23.01.2009

Das Metström Portal wird mit Daten gefüllt 12.01.2009

Weitere Nachrichten...

Benutzername

Passwort

Anmelden

Passwort vergessen?

Neuer Benutzer?



Continuously updated...



Online database – www.ovgu.de/isut/lss/metstroem

The screenshot shows the MetStröm look-up table website interface. The top navigation bar includes links for Website-Übersicht, Barrierefreiheit, Kontakt, and a search bar. The main content area features a banner with the text "MetStröm look-up table". On the left, there are two navigation panes: "Navi" and "Benutzername". The "Navi" pane contains links for News, MetStröm, Members, and Links. The "Benutzername" pane contains fields for Anmelden, Benutzername, Passwort, and a forgot password link. The central content area displays an "Overview" section with a calendar for April 2009 and a list of news items. Below this, three configurations are shown: Configuration M1 (Water injection into Air stream), Configuration M2 (Water injection into Air stream, with a grid to generate controlled turbulence), and Configuration M3 (Water injection into Air stream). Each configuration has a schematic diagram and a corresponding box labeled M1, M2, or M3.

Continuously updated...



Online database – www.ovgu.de/isut/lss/metstroem

The screenshot shows a multi-layered web interface. The top layer is a header with the MetStröm logo, a search bar, and navigation links. Below it is a blue banner with the text 'look-up table'. The main content area has three nested levels of navigation on the left: 'Navi' (News, MetStröm, Members, Links), 'Navi' (News, MetStröm, Configuration M1, Configuration M2, Configuration M3, Configuration M4, Members, Links), and 'Navi' (News, MetStröm, Configuration M1, Configuration M2, Configuration M3, Configuration M4, Members, Links). The central content area displays an 'Overview' of 'Configuration M3', which was last updated by Martin on April 17, 2009. It features a diagram titled 'Water injection' showing air entering a tunnel and creating a 'Vortex generation' at position 'M3'. Below the diagram is a text block about the wind tunnel and test section, followed by a table of measurement data. The right side of the interface includes a calendar for April 2009, a 'Nachrichten' (News) section with various posts, and a sidebar with user login and password recovery options.

Website-Übersicht Barrierefreiheit Kontakt

Suche

MetStröm

look-up table

Startseite News MetStröm Members Links

Sie sind hier: Startseite → MetStröm

Anmelden Registrieren

Navi

News MetStröm Members Links

Anmelden Benutzername Passwort Anmelden

Passwort vergessen? Neuer Benutzer

Navi

News MetStröm Configuration M1 Configuration M2 Configuration M3 Configuration M4 Members Links

Sie sind hier: Startseite → MetStröm → Configuration M3

Anmelden Registrieren

Navi

News MetStröm Configuration M1 Configuration M2 Configuration M3 Configuration M4 Members Links

Configuration M3

erstellt von Martin zuletzt verändert: 17.04.2009 02:29

Configuration M3

Water injection

Air

M3

Vortex generation

Data of Configuration M1. Further information about the wind tunnel and test section is coming soon, in case of any questions please contact me under the e-mail address on the bottom.

Measurement Position	Download	Measured Phase	Measured Values	Method
x = 0	Link	air	u;u'	LDV
x = 0	Link	drops	u;u';d	PDA
x = 200	Link	drops	u;u';d	PDA
x = 400	Link	drops	u;u';d	PDA
y = 0	Link	air	u;v	PIV
y = 0	Link	drops	u;v	PIV

April 2009

So Mo Di Mi Do Fr Sa

1 2 3 4

5 6 7 8 9 10 11

12 13 14 15 16 17 18

19 20 21 22 23 24 25

26 27 28 29 30

Nachrichten

Configuration M1 and M3 completed!! 23.01.2009

Das MetStröm Portal wird mit Daten gefüllt 12.01.2009

Weitere Nachrichten...

Continuously updated...



Online database – www.ovgu.de/isut/lss/metstroem

MetStröm look-up table

Sie sind hier: Startseite → MetStröm

Navi

- News
- MetStröm
- Members
- Links

Anmelden

Benutzername:

Passwort:

Anmelden

Passwort vergessen?

Neuer Benutzer

Navigation

- News
- MetStröm
- Configuration M1
- Configuration M2
- Configuration M3
- Configuration M4
- Members
- Links

Overview

erstellt von Martin zuletzt verändert: 23.04.2009 01:35

Startseite News MetStröm Members Links

Anmelden Registrieren

April 2009

Sa Mo Di Mi Do Fr Sa

1 2 3 4

Sie sind hier: Startseite → MetStröm → Configuration M3

Configuration M3

erstellt von Martin zuletzt verändert: 17.04.2009 02:29

Configuration M3

Water injection

Air

M3

Vortex generation

Data of Configuration M1. Further information about the wind tunnel and test section is coming soon, in case of any questions please come under the e-mail address on the bottom.

Measurement Position	Download	Measured Phase	Measured Values	Met
x = 0	Link	air	u;u'	!
x = 0	Link	drops	u;u';d	!
x = 200	Link	drops	u;u';d	!
x = 400	Link	drops	u;u';d	!
y = 0	Link	air	u;v	!
y = 0	Link	drops	u;v	!

Navi

- News
- MetStröm
- Configuration M1
- Configuration M2
- Configuration M3
- Configuration M4
- M3
- PDA
- Download PDA x = 0 drops
- Download PDA x = 200
- Download PDA x = 400
- Members
- Links

Download PDA x = 0 drops

erstellt von Martin Zschögan zuletzt verändert: 17.04.2009 02:42

Ascii

- x0_II_Diameters.txt
- x0_II_Moments.txt

Distribution

- x0_II.zip

Images

U_Mean [m/s]

x-Koordinaten

z-Koordinaten

x0_UMean_II.bmp

D-Mean (D_{10}) [μm]

x-Koordinaten

z-Koordinaten

x0_D10_II.bmp

Nachrichten

- Configuration M1 and M3 completed! 23.01.2009
- Das MetStröm Portal wird mit Daten gefüllt 12.01.2009

Weitere Nachrichten...

MetStröm Conference 07.06.2011 | 12

Continuously updated...



Online database – www.ovgu.de/isut/lss/metstroem

The screenshot displays two side-by-side views of the MetStröm online database.

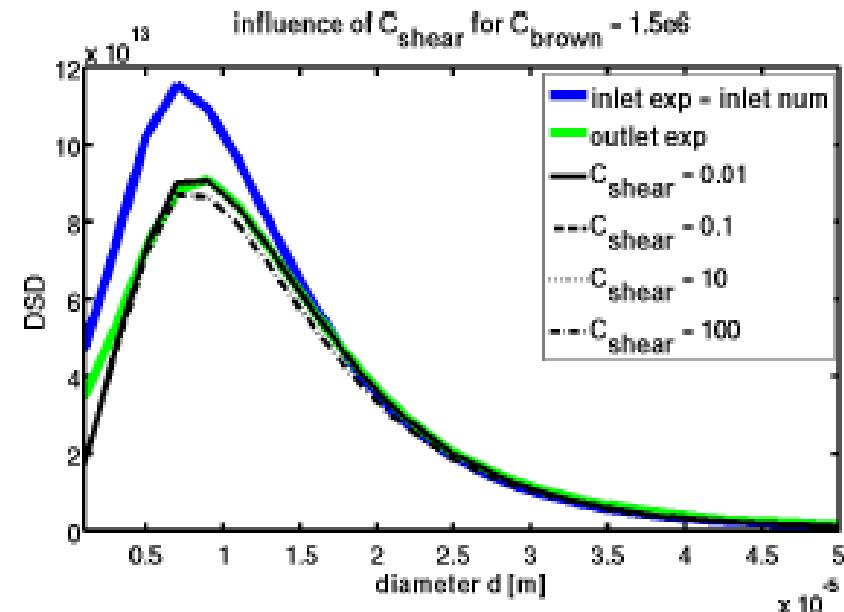
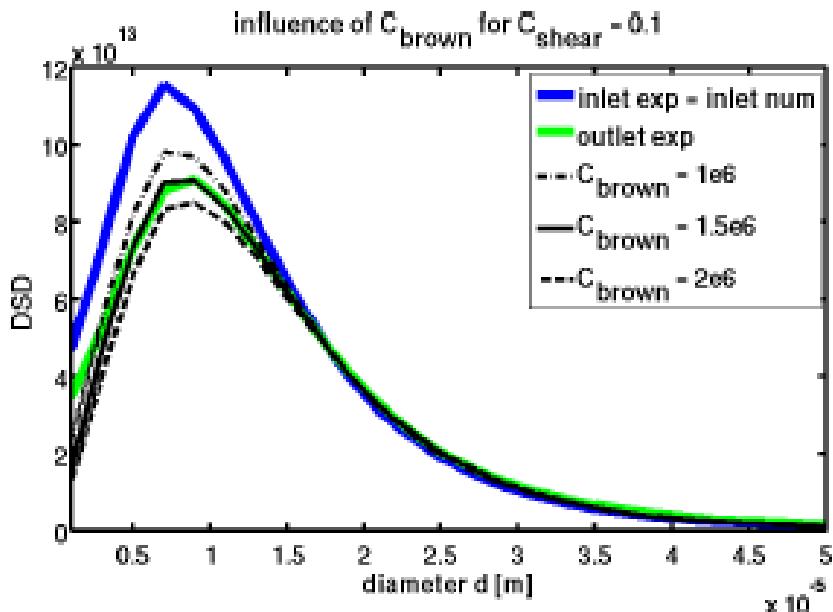
Left View: Shows the homepage with a search bar highlighted by a red oval. Below it is the "look-up table" section, which includes an "Overview" of configurations (Configuration M1-M4) and a detailed view of Configuration M3. Configuration M3 is described as "Water injection" and "Vortex generation". A table lists measurement positions and their corresponding data. The sidebar contains navigation links for News, MetStröm, Members, and Links, along with login and password recovery options.

Right View: Shows a search results page for "Suchresultate" (Search results). It lists 13 articles found, such as "Download LDV x = 0 air" and "Configure M3". To the right is a calendar for April 2009 and a news feed. At the bottom are two heatmaps showing "Mean" and "D-Mean" data across a coordinate system.

Continuously updated...

Companion numerical simulations

Main **interface** between experiments and simulations:
PDA measurements of **droplet number density**
including standard deviation for each size class





Conclusions

- Experiments in **wind tunnel** with key **meteorological conditions**
- Complete experimental **characterization** of the **air flow and water spray**
- Results freely available in a **database** accessible at <http://www.ovgu.de/isut/lss/metstroem>.
- Successful **validation** of companion simulations
- Experimental non-intrusive **measurement** of **droplet collision rate**
 - Comparison with theoretical predictions
 - The measured collision rates are higher than predicted by theory, typically by a factor of 2 to 6.



Thank you for your attention!



<http://www.ovgu.de/isut/lss/metstroem>
<http://metstroem.mi.fu-berlin.de/>

bordas@ovgu.de