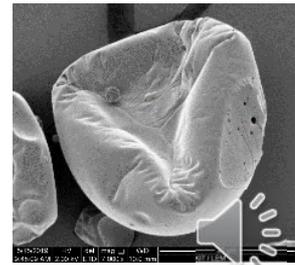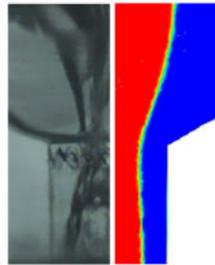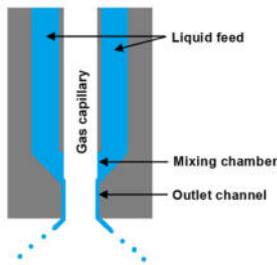# Spray-Drying of Pastes with ACLR-Nozzle for Process Intensification

Volker Gaukel, Sebastian Höhne, Miguel Ballesteros
2023 IFPRI Annual Meeting

Liquid feed
Gas capillary
Mixing chamber
Outlet channel

KIT – The Research University in the Helmholtz Association

www.kit.edu

KIT– Karlsruhe Institute of Technology

37 Spinoffs and Startups

5 Campuses **– 200** ha area

367 Trainess

385 Professors and executive scientists

22,225 Students

300 Buildings with a usable area of **492,000 m²**

3,100 Doctoral students

KIT budget 2021
EUR 1090,7 million

41% Third-party funds
31% State funds
28% Federal funds

Status: Mai 2021

51 Patent applications

9,783 Employees

1,405 international scientists

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Science Organization of KIT

Division I Biology, Chemistry, and Process Engineering	**Division II** Informatics, Economics, and Society	**Division III** Mechanical and Electrical Engineering	**Division IV** Natural and Built Environment	**Division V** Physics and Mathematics
20 **Institutes**/Institutions	26 **Institutes**/Institutions	34 **Institutes**/Institutions	23 **Institutes**/Institutions	21 **Institutes**/Institutions
2 KIT Departments	3 KIT Departments	2 KIT Departments	2 KIT Departments	2 KIT Departments
2 Helmholtz Programmes	2 Helmholtz Programmes	3 Helmholtz Programmes	1 Helmholtz Programme	3 Helmholtz Programmes

Executive Board

President — Vice President Research — Vice President Higher Education and Academic Affairs — Vice President Transfer and International Affairs — Vice President for Finance, Human Resources and Infrastructure — Vice President Digitalization and Sustainability

Service Units

8 KIT Centers

Volker Gaukel: Spray-Drying of Pastes with ACLR-Nozzle for Process Intensification

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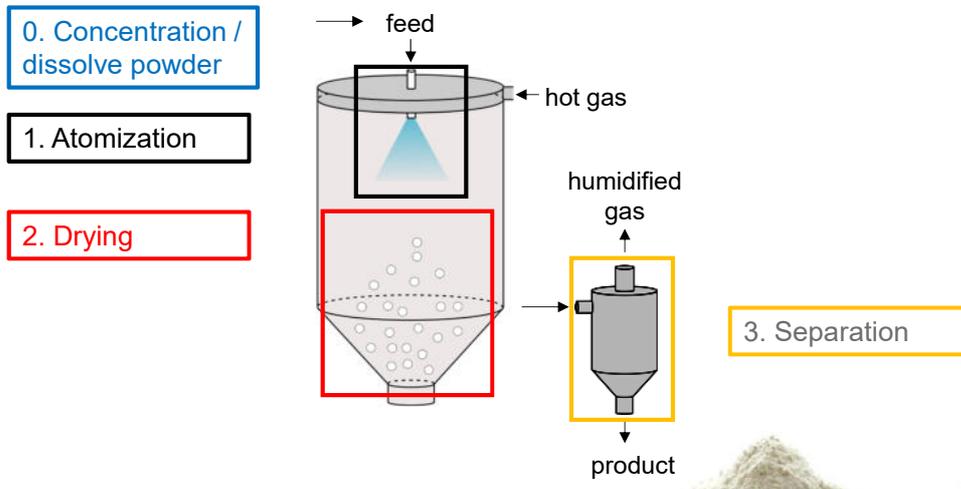**Prof. Dr.-Ing. Heike P. Karbstein**

Administration

PD Dr. rer. nat. Volker Gaukel — Research Manager

Klaudia Merkle — Secretary/ Administration for Projects and Teaching

Renate Genzer — Secretary/ Accounting

Research

Design of Efficient Drying and Freezing Processes

PD Dr. rer. nat. Volker Gaukel — Research Manager

Till Sickert — Microwave assisted Freeze Drying

Miguel Ballesteros[1] — CFD Modelling of two Phase Flow in Spray Nozzels

Sebastian Höhne — Spray Drying of Emulsions for Microencapsulation

Julian Gerhäuser — Molecular Modelling of Ice/Water Interfaces

Extrusion of Biopolymeric Materials

Prof. Dr.-Ing. Heike P. Karbstein — Research Director

Felix Ellwanger — Flow Characteristics of Highly Concentrated Protein Systems

Laurids Pernice — Texturizing Microbial and Plant Proteins via Extrusion

Emulsion technology

Functionality of Biopolymers

Dr.-Ing. Ulrike van der Schaaf — KIT Associate Fellow

Laura Riedel — Single cell and plant proteins in emulsions and gels

Désirée Martin — Interfacial properties of Gum Arabic

Encapsulation and Microfluidics

Nico Leister — Senior Research Scientist

Eva Rütten — Flow Conditions in SHM Valves

Philipp Schochat — Oil phase structuring in emulsions

[1]financed externally

Laboratory/Technical

Nina Weis — Markus Fischer — Jürgen Kraft — Kerstin Sauther — Lydia Schütz — Annette Berndt

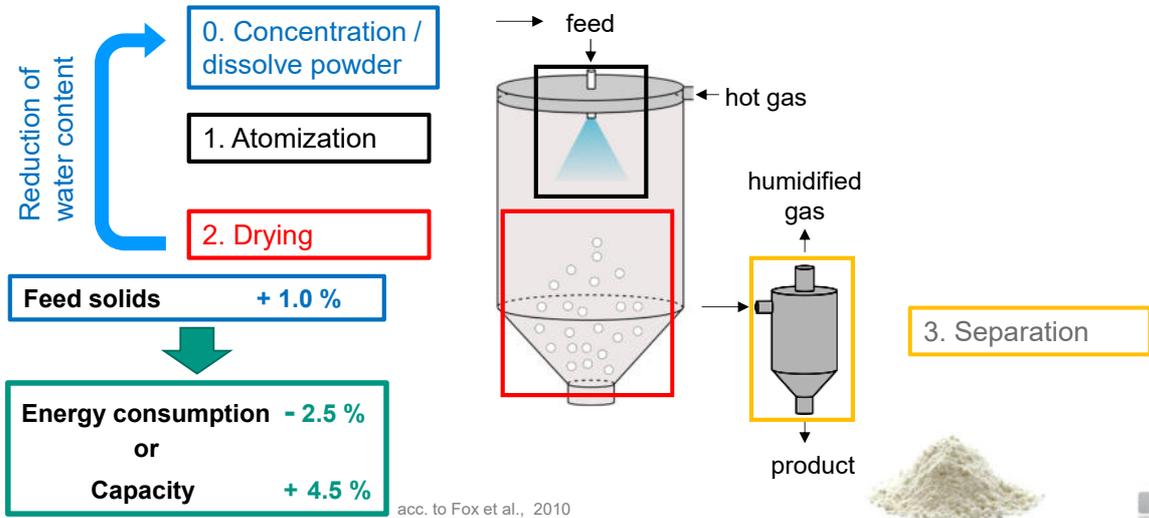# The spray drying process can be divided in different processing steps:

0. Concentration / dissolve powder

1. Atomization

2. Drying

3. Separation

feed

hot gas

humidified gas

product

Volker Gaukel: Spray-Drying of Pastes with ACLR-Nozzle for Process Intensification

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The spray drying process can be divided in different processing steps:

Reduction of water content

0. Concentration / dissolve powder

1. Atomization

2. Drying

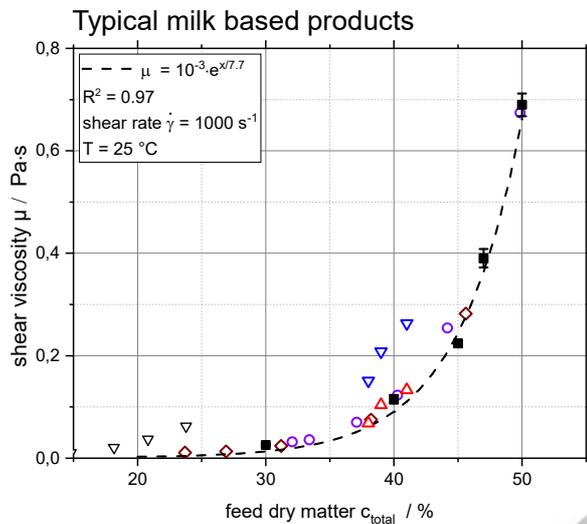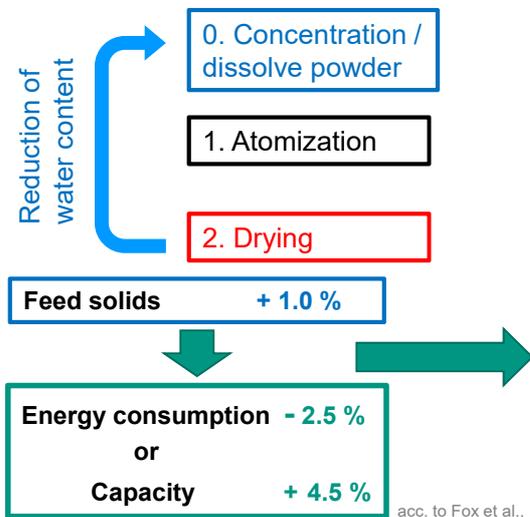3. Separation

feed

hot gas

humidified gas

product

Drying step has a high energy demand:

- theoretically 2250 MJ/t

- In reality: up to 100 % higher

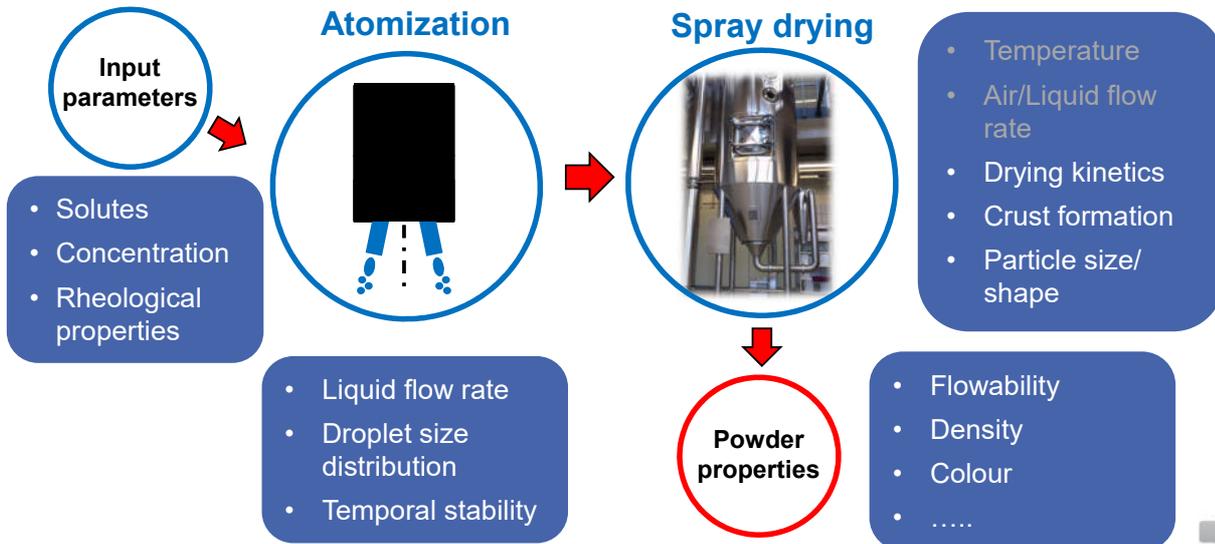- Energy recovery ist partly possible but complex (e. g. high temperature heat pumps)

Volker Gaukel: Spray-Drying of Pastes with ACLR-Nozzle for Process Intensification

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The spray drying process can be divided in different processing steps:

Reduction of water content

- 0. Concentration / dissolve powder
- 1. Atomization
- 2. Drying

Feed solids	+ 1.0 %

Energy consumption	- 2.5 %
or	
Capacity	+ 4.5 %

acc. to Fox et al., 2010

feed

hot gas

humidified gas

3. Separation

product

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Higher feed concentration complicates atomization

Reduction of water content

- 0. Concentration / dissolve powder
- 1. Atomization
- 2. Drying

Feed solids	+ 1.0 %

Energy consumption	- 2.5 %
or	
Capacity	+ 4.5 %

acc. to Fox et al., 2010

Typical milk based products

$\mu = 10^{-3} \cdot e^{x/7.7}$
$R^2 = 0.97$
shear rate $\dot{\gamma} = 1000\ s^{-1}$
$T = 25\ °C$

shear viscosity μ / Pa·s

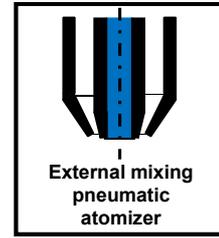feed dry matter c_{total} / %

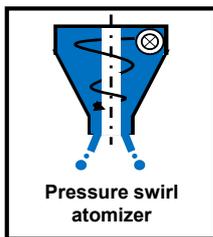Institute of Process Engineering in Life Sciences
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Process steps are connected

Atomization

Spray drying

Input parameters

Solutes
Concentration
Rheological properties

- Liquid flow rate
- Droplet size distribution
- Temporal stability

Powder properties

- Temperature
- Air/Liquid flow rate
- Drying kinetics
- Crust formation
- Particle size/ shape

- Flowability
- Density
- Colour
- …..

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Different types of atomizers are used:

Pressure swirl nozzle

➕ Energy efficient atomization

➖ Very limited max. viscosity

Process and scale depended use

External mixing pneumatic atomizer

➕ Atomization of high viscous liquids

➖ High atomization gas consumption

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Is it possible to atomize high viscous liquids with a lower gas demand?

Pressure swirl atomizer

?

External mixing pneumatic atomizer

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The Air-Core-Liquid-Ring-atomizer combines both concepts

Pressure swirl atomizer

Enforced annular flow inside the exit orifice

ACLR-atomizer
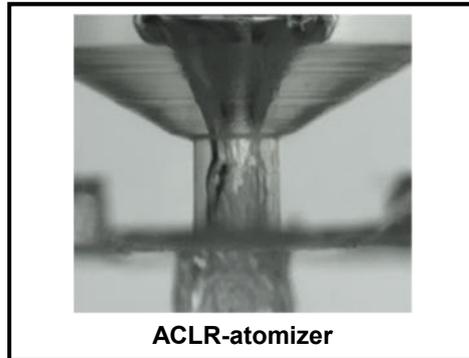
External mixing pneumatic atomizer

[Stähle, P; Gaukel, V; Schuchmann, HP (2017): *J. of Food Process Eng.* 40, 1-9]

[Stähle, P; Schuchmann, HP; Gaukel, V (2017): *J. of Food Process Eng.* 40, 1-12]

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The Air-Core-Liquid-Ring-atomizer combines both concepts

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[Stähle, P; Gaukel, V; Schuchmann, HP (2017): *J. of Food Process Eng.* 40, 1-9]

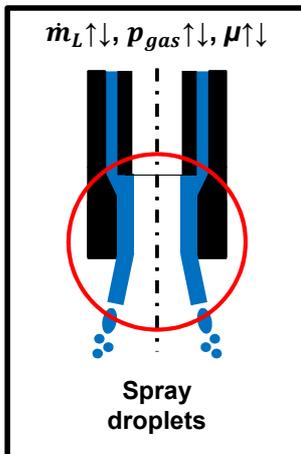[Stähle, P; Schuchmann, HP; Gaukel, V (2017): *J. of Food Process Eng.* 40, 1-12]

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Some principles results so far

$$\dot{m}_L \uparrow\downarrow,\ p_{gas} \uparrow\downarrow,\ \mu \uparrow\downarrow$$

Spray droplets

The liquid film thickness determines the performance of ACLR atomization

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Some principles results so far

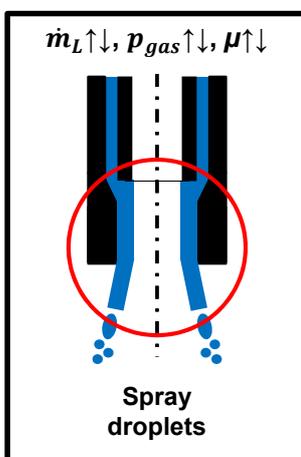$\dot{m}_L \uparrow\downarrow, p_{gas} \uparrow\downarrow, \mu \uparrow\downarrow$

Spray droplets

The liquid film thickness determines the performance of ACLR atomization

⬇

Thinner liquid films lead to smaller spray droplet sizes

Volker Gaukel: Spray-Drying of Pastes with ACLR-Nozzle for Process Intensification

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Some principles results so far

$\dot{m}_L \uparrow\downarrow, p_{gas} \uparrow\downarrow, \mu \uparrow\downarrow$

Spray droplets

The liquid film thickness determines the performance of ACLR atomization
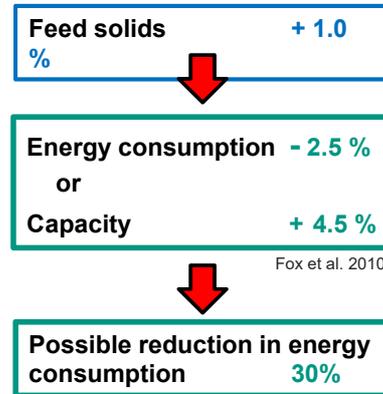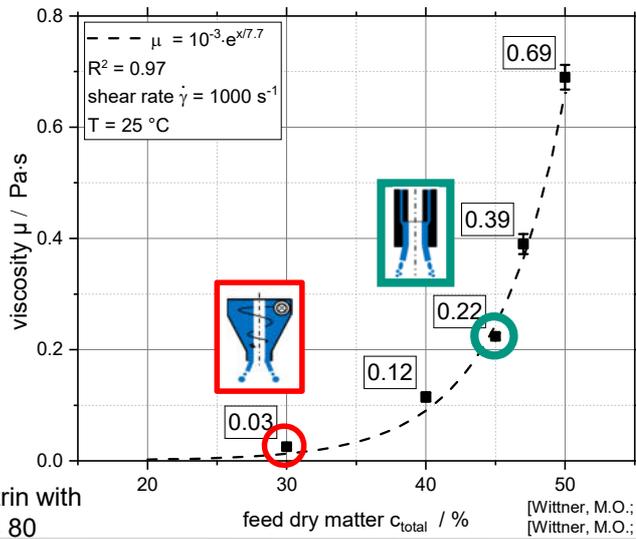
⬇

Thinner liquid films lead to smaller spray droplet sizes

Increasing stability of liquid film thickness leads to more stable spray droplet size distributions

[Wittner, M.O.; Ballesteros, M.A.; Link, F.; Karbstein, H.P.; Gaukel, V. (2019): processes 7, 616]

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Principle application of ACLR atomization offers energy savings of around 30 %

$\mu = 10^{-3} \cdot e^{x/7.7}$
$R^2 = 0.97$
shear rate $\dot{\gamma} = 1000 \text{ s}^{-1}$
$T = 25 \text{ °C}$

Maltodextrin with
2 % WPC 80

Feed solids	+ 1.0 %
Energy consumption	- 2.5 %
or	
Capacity	+ 4.5 %

Fox et al. 2010

Possible reduction in energy consumption   30%

[Wittner, M.O.; Karbstein, H.P.; Gaukel, V. (2020). Drying Technology 38 (12), 1323-1331]
[Wittner, M.O.; Schuchmann, H.P.; Gaukel, V. (2017). Food Lab (2), 53-57]

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Scale up is possible
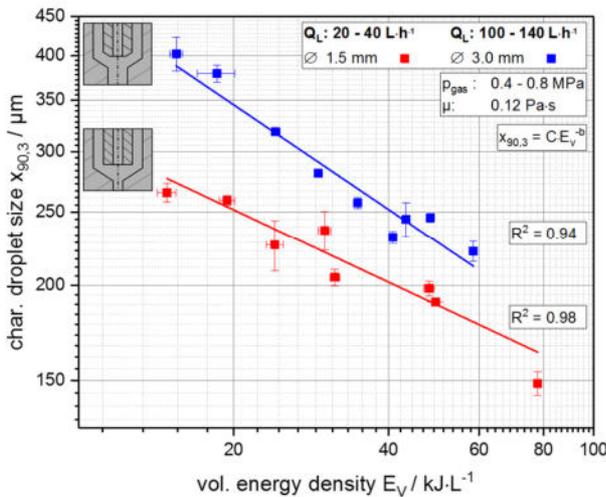
Increasing the feed flow by 4-5 with simple orifice scale up

Increase of char. droplet size by 30 %

Increasing of energy input by 50 %

[Wittner, M.O.; Karbstein, H.P.; Gaukel, V. (2019): processes 7, 139]

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Open Tasks

Atomization and drying of feeds with higher viscosity (pastes)

- **Further improve the spray stability with:**
  - Geometrical optimizations
  - Process paramater adoptions
- **Further Development of scale up concepts**

By means of validated CFD

- **Investigation of the drying performance of pastes for adopted process conditions**

By single droplet drying

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Working schedule for current project

Spray-Drying of Pastes with ACLR-Nozzle for Process Intensification

Project year					1			2			3	
Quarter	I	II	III	IV	I	II	III	IV	I	II	III	IV
WP 1: Atomization with the ACLR nozzle (validated CFD model)	■	■	■	■	■	■						
WP 2: Evaluation of the impact of composition and morphology on drying kinetics			■	■	■	■	■	■				
WP 3: Industrial applicability of the ACLR nozzle for spray-drying									■	■	■	■

current state

Volker Gaukel: Spray-Drying of Pastes with ACLR-Nozzle for Process Intensification

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WP 1: Atomization with the ACLR nozzle

To examine the suitability and limitations of the ACLR nozzle for the atomization of highly viscous liquids and pastes

Goal: Investigate how the liquid rheology affects the…

- …spray stability
- …droplet size distribution
- …operational requirements

Methods:
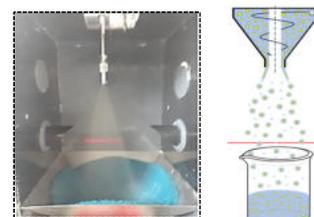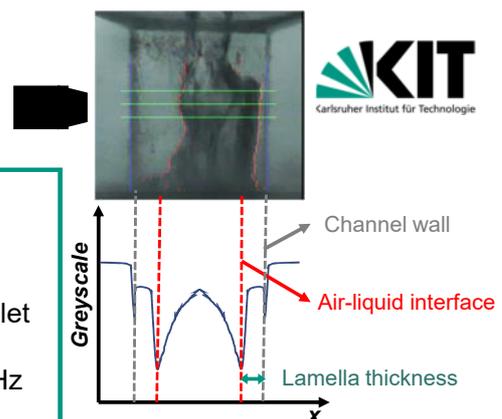
- Computational Fluid Dynamics
- Atomization rig

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Atomization rig

Features:
- Gas pressure = max. 8 bar
- Volume flow rate = 40 l/h
- Laser diffraction: Spray droplet sizes 5-2000 µm
- High speed imaging at 20 kHz

What we measure:
- Spray droplet size
- Internal lamella thickness
- Spray angle

Channel wall

Air-liquid interface

Lamella thickness

Greyscale

x

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Characterization of model system: Extrapolating to higher viscosities requires more rheological information

Maltodextrin solutions (C*Dry MD 01910)

Maltodextrin solutions (C*Dry MD 01958)
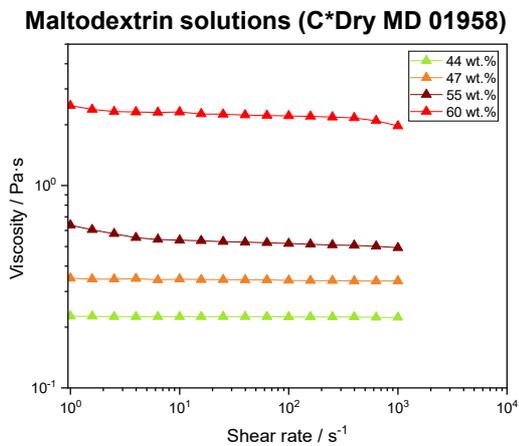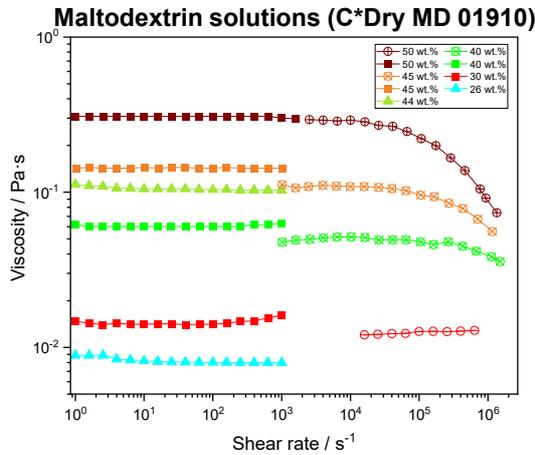
Measurements with capillary rheometer ongoing

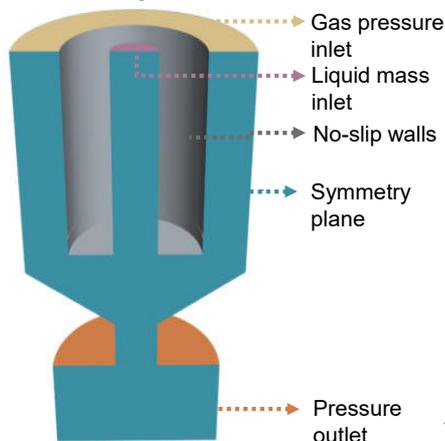Institute of Process Engineering in Life Sciences
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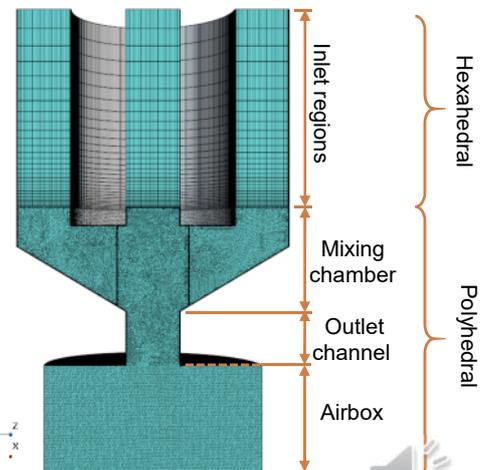

CFD Model development

Model (ANSYS Fluent)

- **Volume of Fluid:** single phase flow with avg. properties
- **Interface:** Discontinuity in the volume fraction field
- **Liquid:** constant density and Newtonian
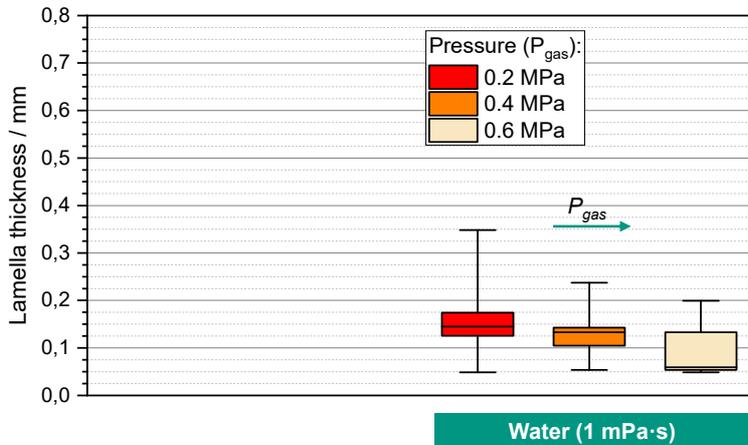- **Gas:** ideal gas model
- **Turbulance:** RANS or LES

Boundary Cond.

- Gas pressure inlet
- Liquid mass inlet
- No-slip walls
- Symmetry plane
- Pressure outlet

Mesh

Inlet regions — Hexahedral

Mixing chamber
Outlet channel
Airbox — Polyhedral

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Lamella thickness: Decreasing in size and variation with increasing gas pressure
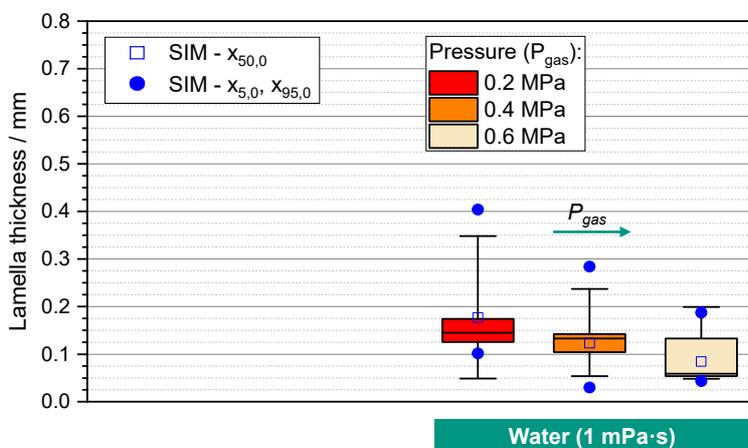
Simulated on ANSYS Fluent:
- Exclusively internal flow
- k-ω SST turbulence model

Water (1 mPa·s)

M. A. Ballesteros Martinez and V. Gaukel (2023). *Flow, Turbulence and Combustion.*

Flow rate (Q_L): 40 L/h

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Lamella thickness: Good agreement of CFD with experimental data

Simulated on ANSYS Fluent:
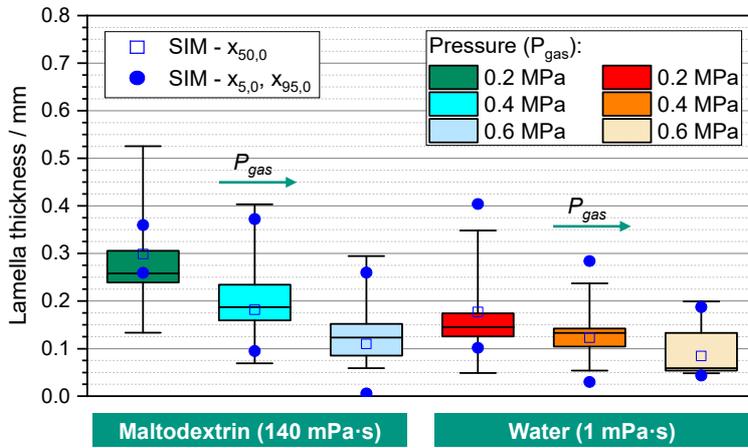- Exclusively internal flow
- k-ω SST turbulence model

SIM results fit with EXP:
- Avg. RE for $x_{50,0}$ ~ 10%
- Avg. RE for $x_{95,0}$ ~ 15%c

Water (1 mPa·s)

M. A. Ballesteros Martinez and V. Gaukel (2023). *Flow, Turbulence and Combustion.*

Flow rate (Q_L): 40 L/h

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Time-averaged flow behaviour is predicted well by the model

Maltodextrin (140 mPa·s) — **Water (1 mPa·s)**

Simulated on ANSYS Fluent:
- Exclusively internal flow
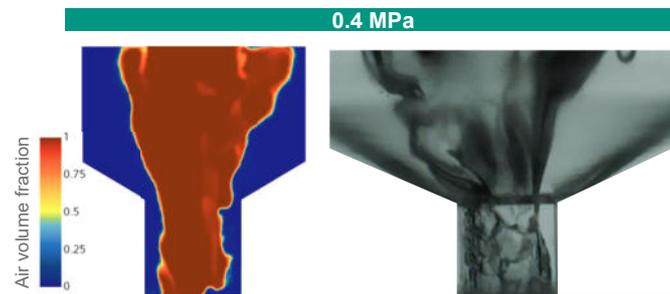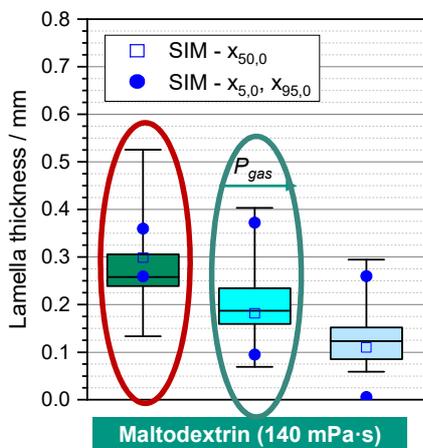- k-ω SST turbulence model

SIM results fit with EXP:
- Avg. RE for $x_{50,0}$ ~ 10%
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Flow rate (Q_L): 40 L/h

M. A. Ballesteros Martinez and V. Gaukel (2023). *Flow, Turbulence and Combustion*.

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Time-averaged flow behaviour is predicted well by the model
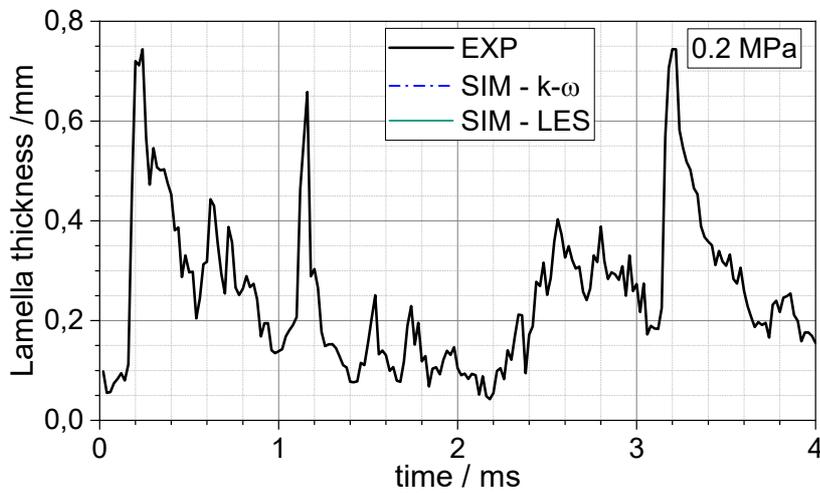

0.4 MPa

Both in SIM and EXP:
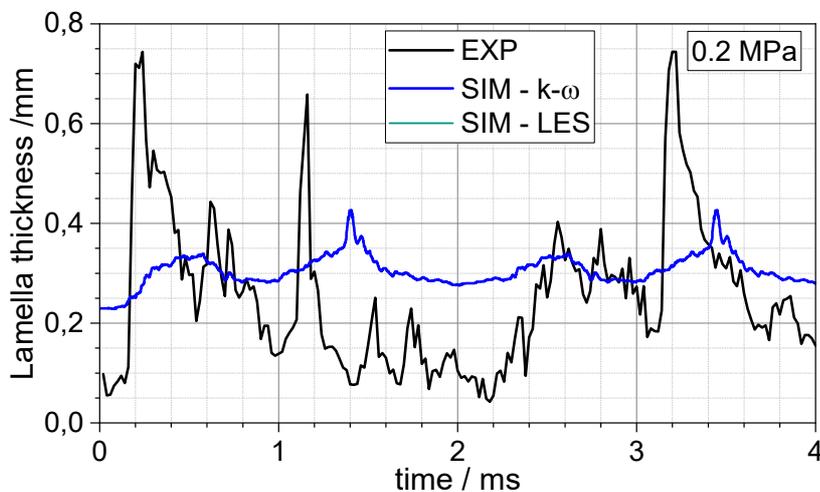
↑ Flow variation with ↑ Viscosity and ↓ Pressure

μ: 140 mPa·s Q_L: 40 L/h

M. A. Ballesteros Martinez and V. Gaukel (2023). *Flow, Turbulence and Combustion*.

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The moment-to-moment behaviour of the lamella thickness is better captured with LES

Volker Gaukel: Spray-Drying of Pastes with ACLR-Nozzle for Process Intensification

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Volker Gaukel: Spray-Drying of Pastes with ACLR-Nozzle for Process Intensification

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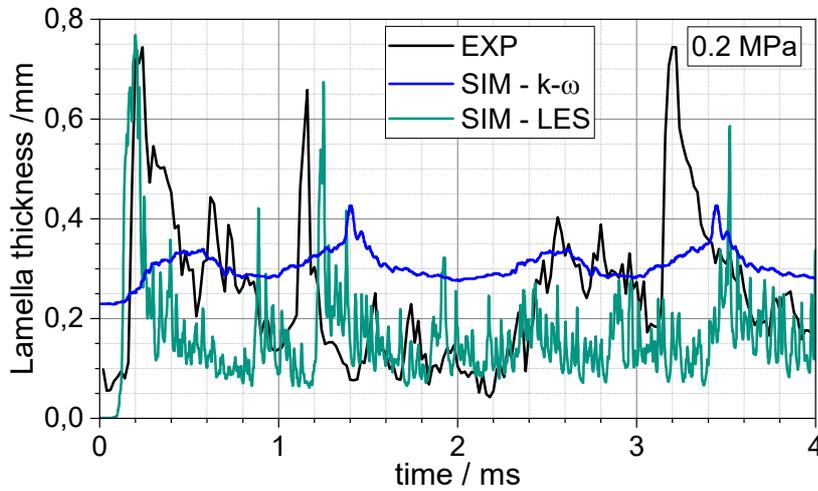
The stability of external flow near the nozzle exit can also be visualized with CFD => Spray angle validation

Volker Gaukel: Spray-Drying of Pastes with ACLR-Nozzle for Process Intensification

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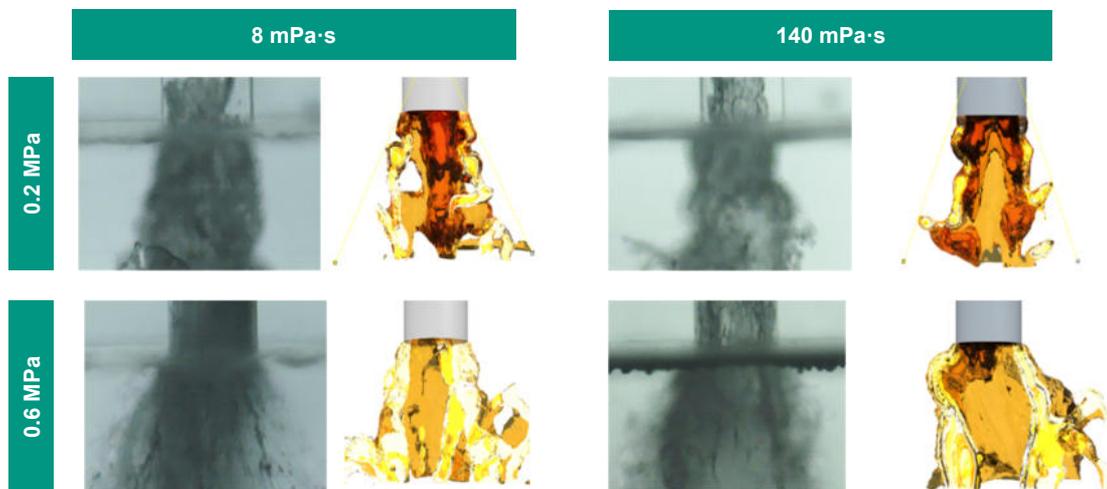
Validation of external flow parameters by spray angle

Pressure / MPa	Spray angle			
	8 mPa·s		140 mPa·s	
	Experimental	Simulation	Experimental	Simulation
0.2	41 ± 4°	44°	35 ± 6°	42°
0.4	56 ± 2°	58°	44 ± 4°	45°
0.6	70 ± 4°	70°	51 ± 4°	67°

Next steps:

- Implement a viscosity model in the simulation
- Simulate higher viscosities
- Optimize nozzle (geometry, operating cond.)

Volker Gaukel: Spray-Drying of Pastes with ACLR-Nozzle for Process Intensification

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WP 2: Evaluation of the impact of composition and morphology on drying kinetics

Mechanistic investigation of the impact of drying rate and total solids content in a model drying set-up
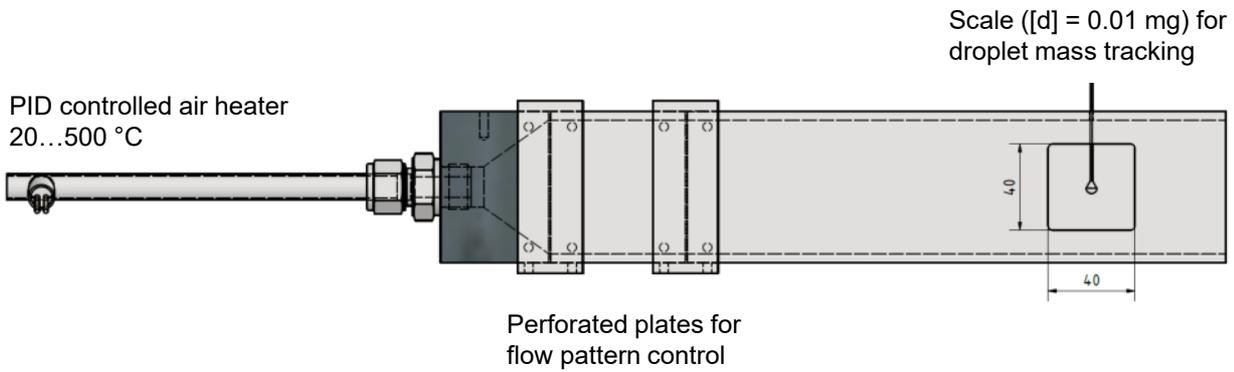
Goal: Investigation of the…

- …drying kinetics
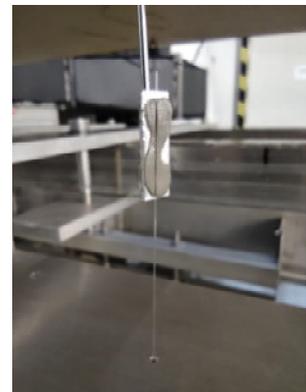- …skin formation
- …morphology development

Methods:
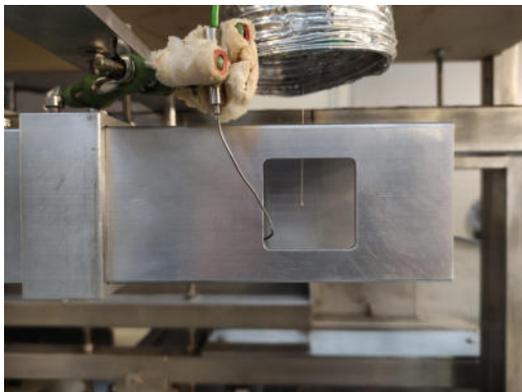
- Hanging droplet
- Sessile droplet
- Thin film drying

Volker Gaukel: Spray-Drying of Pastes with ACLR-Nozzle for Process Intensification

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Schematic set-up of the drying channel

Scale ([d] = 0.01 mg) for droplet mass tracking

PID controlled air heater 20…500 °C

Perforated plates for flow pattern control

Volker Gaukel: Spray-Drying of Pastes with ACLR-Nozzle for Process Intensification

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Assembly of the drying channel

Volker Gaukel: Spray-Drying of Pastes with ACLR-Nozzle for Process Intensification

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Contour analysis can be used to track droplet size

Original   Binarization   Contour
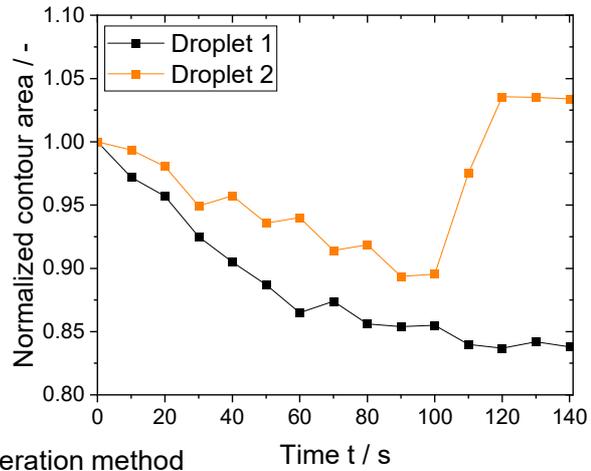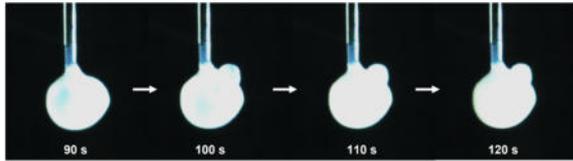
Optimization of…

- the best combination of filament and droplet generation method
- droplet mass measurements
- the drying tunnel (measuring technology, insulation,…)

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Thank you for your attention!

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