
Quelle: voestalpine AG

Defined setup of heat transfer profiles in spray nozzle fields for optimization of heat treatment in continuous strip plants

IGF Project No. 20782 BG

4th Project Advisory Committee Meeting

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31th May, 2023

Project Framework

Project advisory committee (PAC)

Project duration: 08/2019 – 07/2023 **(3rd extension)**

PAC chairperson: *Dr. Tobias Mertens, Otto Junker GmbH*

Project Framework

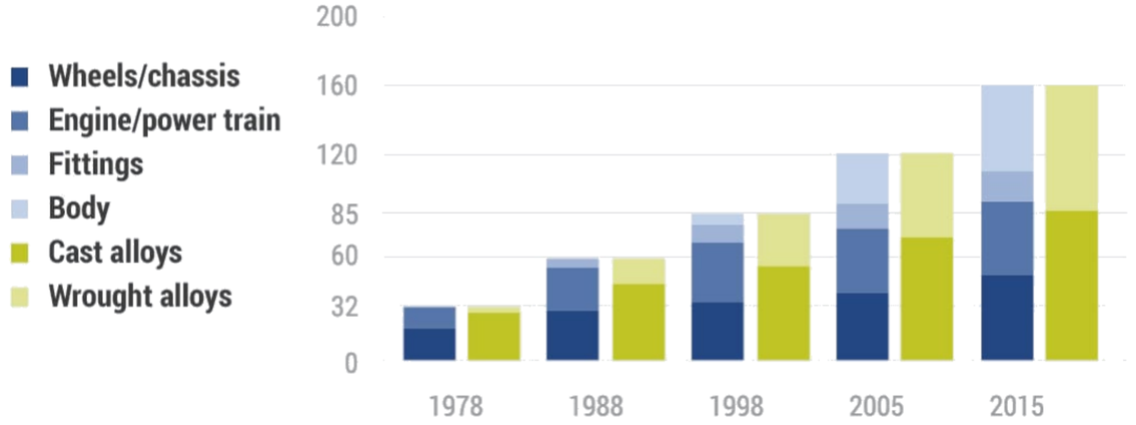
Gantt chart

			Duration (project month)																													
		FSt	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
WP 1	**1:** Modification/construction of the test rigs	IOB																														
		LTV																														
WP 2	**2:** Development of measuring principle	IOB																														
		LTV																														
WP 3	**3.1:** Investigation of heat transfer top side	IOB																														
		LTV																														
	3.2: Investigation of heat transfer bottom side	IOB																														
		LTV																														
WP 4	**4:** Flow investigation on the heat transfer test rig	IOB																														
		LTV																														
WP 5	**5:** Parameter study on the flow behaviour in the nozzle field	IOB																														
		LTV																														
WP 6	**6:** Heat transfer on moving samples	IOB																														
		LTV																														
WP 7	**7:** Validation on test facility in a company	IOB																														
		LTV																														
WP 8	**8:** Additional parameter variation	IOB																														
		LTV																														
WP 9	**9:** Reports, publications, coordination	IOB																														
		LTV																														

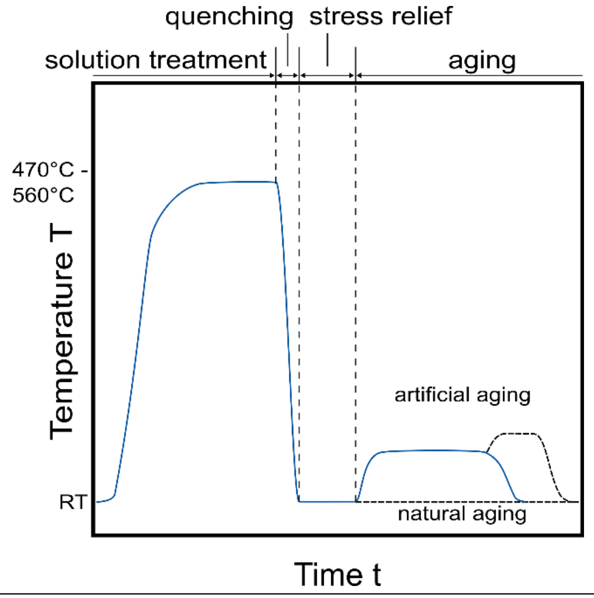
Research Project

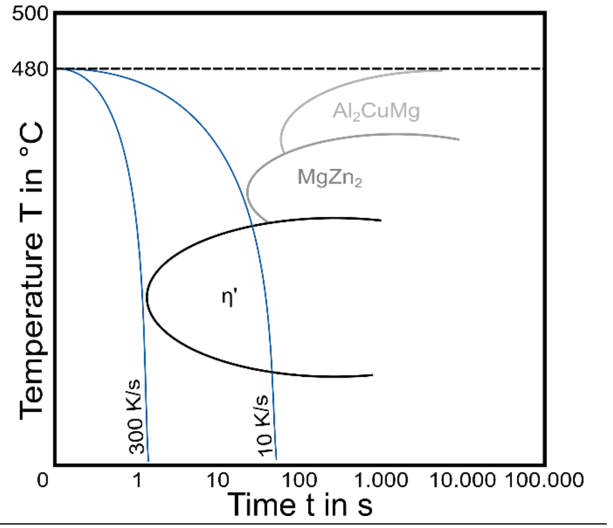
Motivation

- Increasing demand for high-strength materials, e.g. in the automotive or aerospace industry
  - aluminum content of cars produced in Europe between 1978 and 2015 went up from 32 kg to 160 kg
- Production via tempering process
  - Cooling as a central component of heat treatment
  - High cooling rates are set by the materials and determine the mechanical properties
    - 2XXX, 6XXX, 7XXX Al-Alloys
    - E.g. AA7150 with up to 300 K/s
    - Water as coolant needed



source: aluinfo.de/mobility

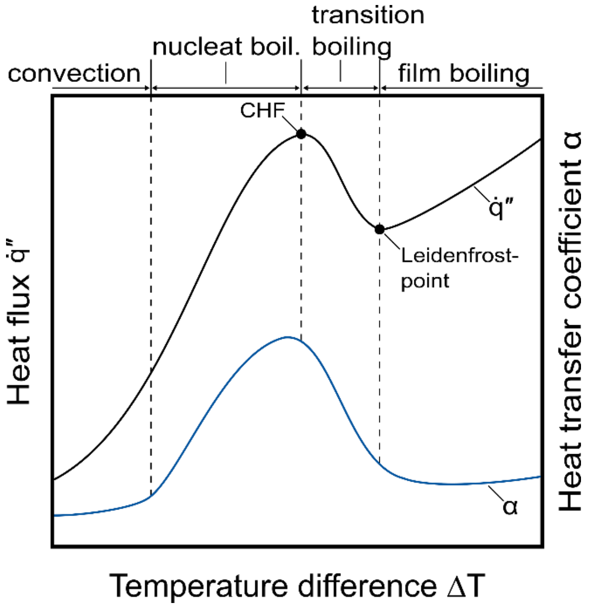


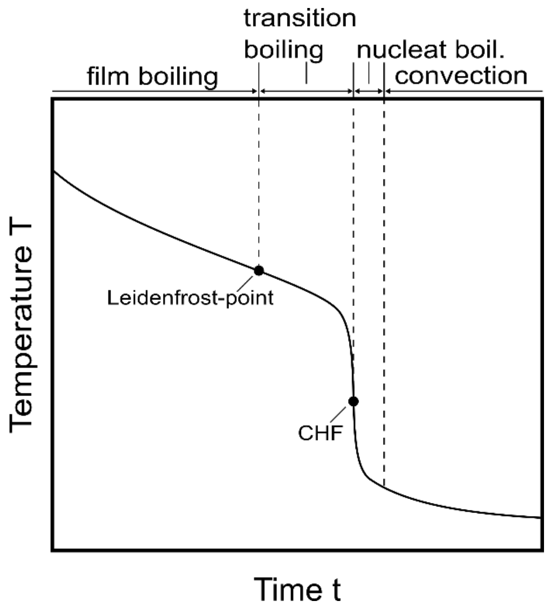


Research Project

Motivation

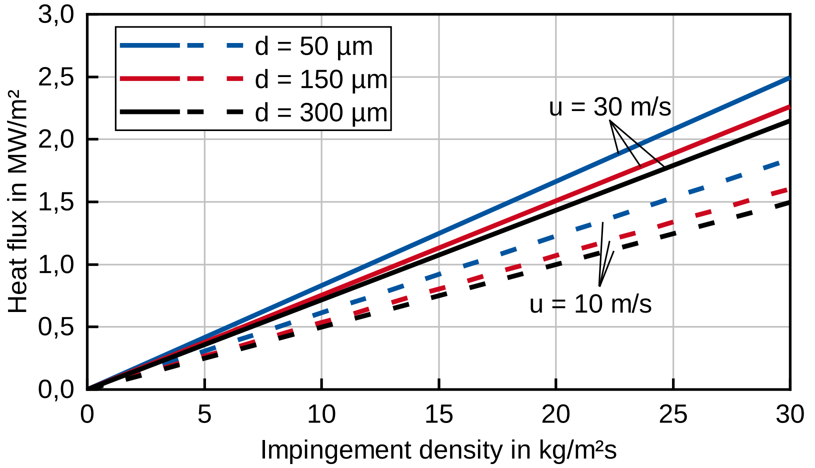
- Four characteristic phases during quenching
- High temperature dependent heat transfers
- Local gradients of heat transfer
- Large dimensions
- Continuous process
- Temperature sensitive component shapes
- Changing annealing recipes
- Lots of depended und independent influencing factors
  - Nozzles, nozzle pressure, nozzle arrangement, impingement density
  - Water quality
  - Strip speed, strip width
  - Draining water, stagnation points, overlap areas
- …





The great challenge with water-cooling is to provide homogeneous cooling conditions while ensuring flexible cooling rates

Research needed!



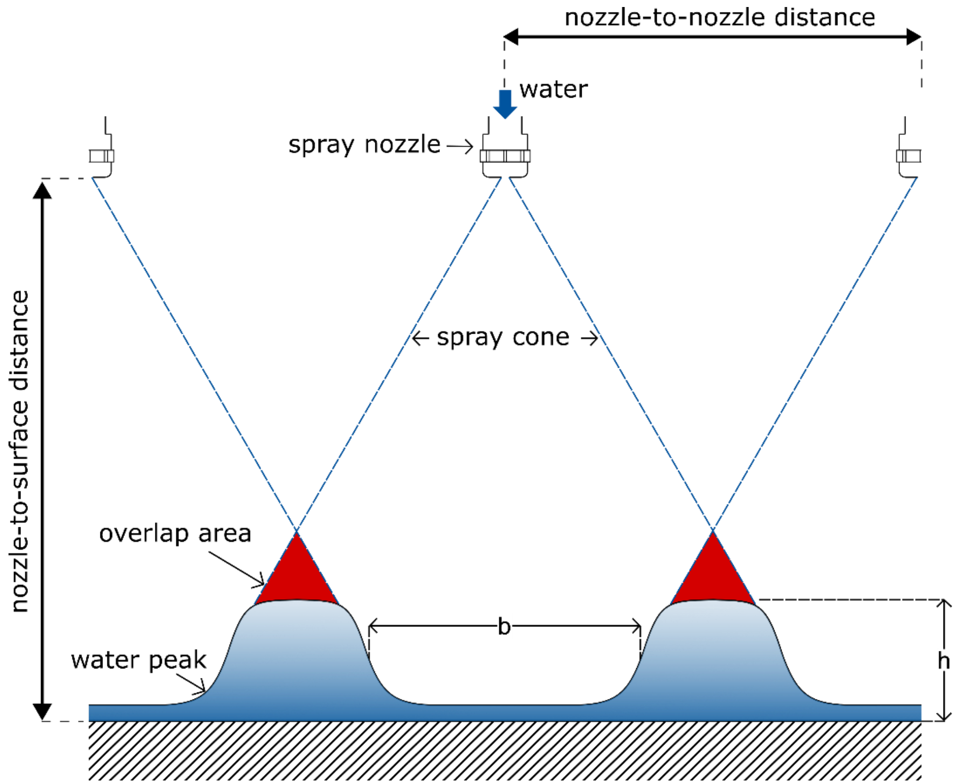
Research Project

Tasks

The heat transfer of single nozzles is well known and investigated while the heat transfer in nozzle fields with its interaction between the nozzles is not well investigated

Questions heat transfer – nozzle fields:

- How does the flow develop on the strip surface?
  - How do the nozzles influence each other?
  - How do stagnation points and water fronts develop on the each side of the horizontal strips?
  - What is the influence of strip-speed on the formation of those stagnation fronts and on the heat transfer?
- How is the heat transfer affected by this?
- Is it possible to adjust and homogenize the heat transfer by varying certain parameters?



Structure

Examination of spray nozzle fields

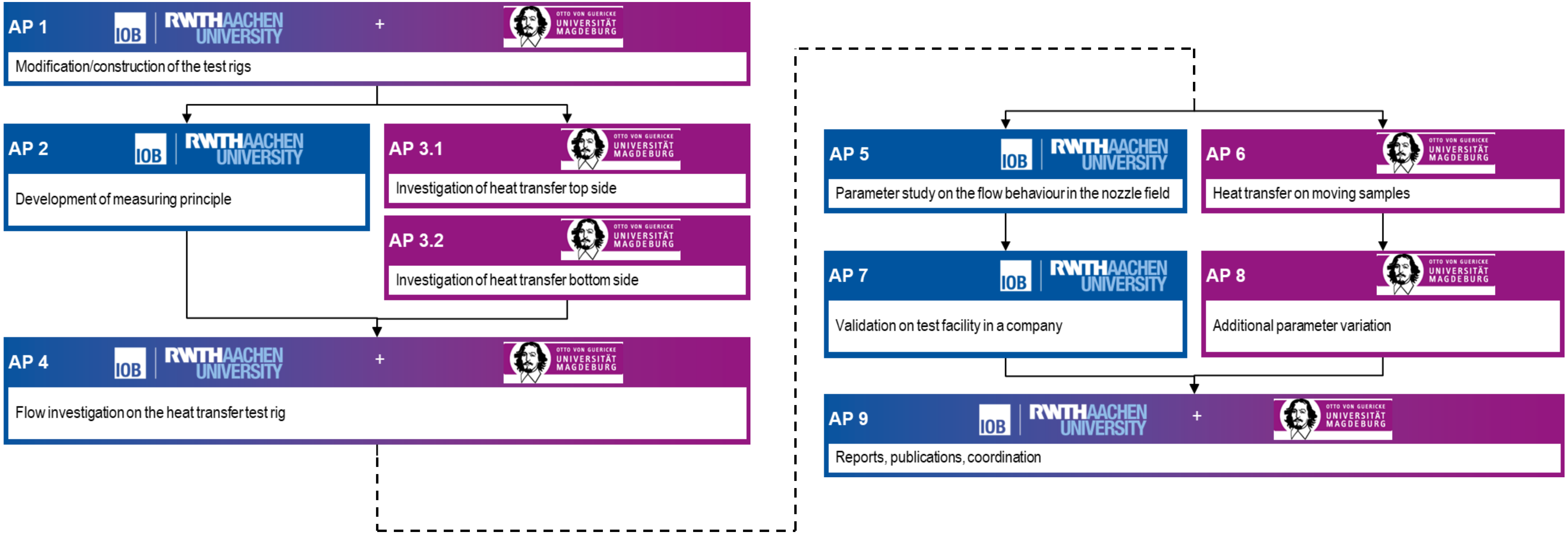
flow determination on the surface

determination of HTC on moving specimens

correlation of flow & HTC

Goal: examination of local and integral heat-transfer-coefficients and correlation with the spray phenomena on the strip surface while cooling in nozzle fields

Structure



Institut für Industrieofenbau und Wärmetechnik

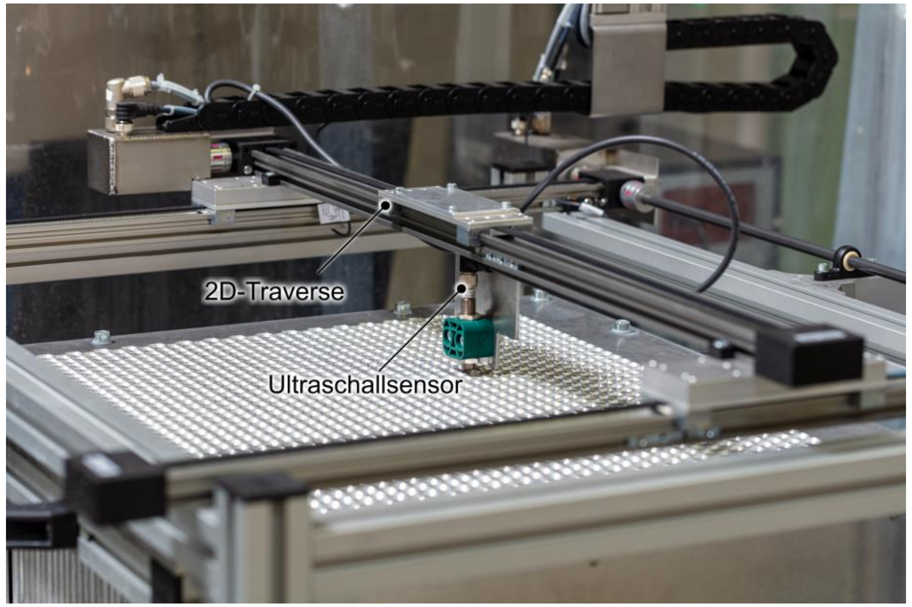
Project Status

Target-performance comparison

Work Package	Progress	Status
WP 1: Modification/construction of the test rigs	Act: 96 % Tar: 100 %	
WP 2: Development of measuring principle	Act: 100 % Tar: 100 %	
WP 3: Investigation of heat transfer (stationary sheet)	Act: 80 % Tar: 100 %	
WP 4: Flow investigation on the heat transfer test rig	Act: 0 % Tar: 100 %	
WP 5: Parameter study on the flow behaviour in the nozzle field	Act: 90 % Tar: 100 %	
WP 6: Investigation of heat transfer (moving sheet)	Act: 10 % Tar: 100 %	
WP 7: Validation on test facility in a company	Act: 0 % Tar: 100 %	

Test rigs for determining the flow (IOB)

- **Impact force**
  - Force sensor mounted flush in the surface
  - Determination of the impact force at any point in the setup possible (measurement carried out along two axes)
- **Ultrasonic sensor**
  - Ultrasonic sensor with measurement tube is positioned above the surface
  - Determination of the water peak height possible at any point in the setup
- **Patternator**
  - 3D arrangement of tubes (1330 measuring points) with automatic level determination with ultrasonic sensor
  - Determination of impingement density
- **Optical measurement method**
  - Camera recordings with subsequent image processing
  - Determination of flow formation



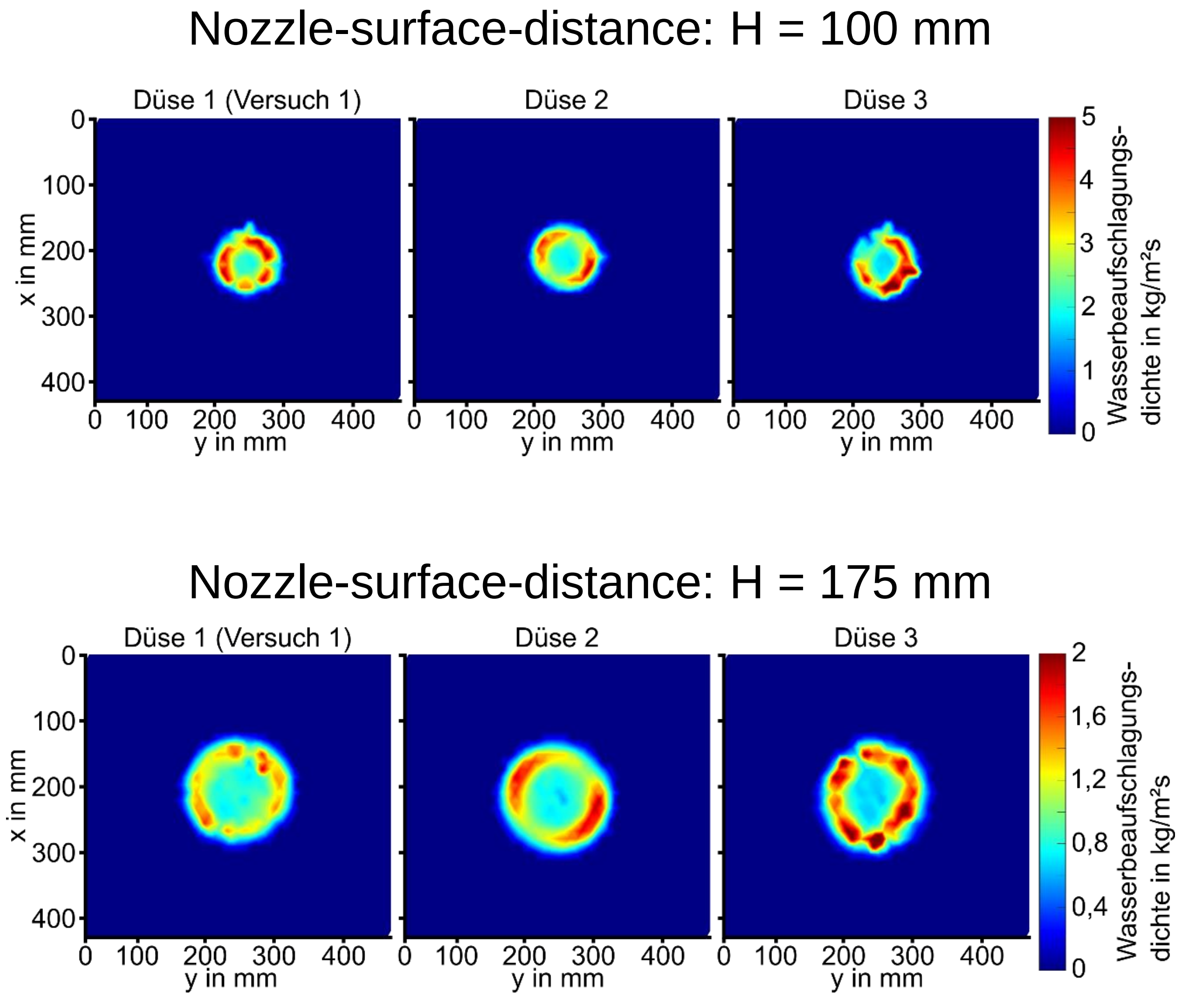
Flow on stationary surface

Single full cone nozzle

- Single full cone nozzles investigated with Patternator
  - Varying nozzles, nozzle pressure and nozzle-surface-distance
  - Nozzle pressure: p = 5 bar
  - Determination of impingement density
  - Ring-shaped area with higher impingement density

- Slightly different spray pattern for each nozzle
  - Upstream flow situation
  - Nozzle state (usage time, clogging)

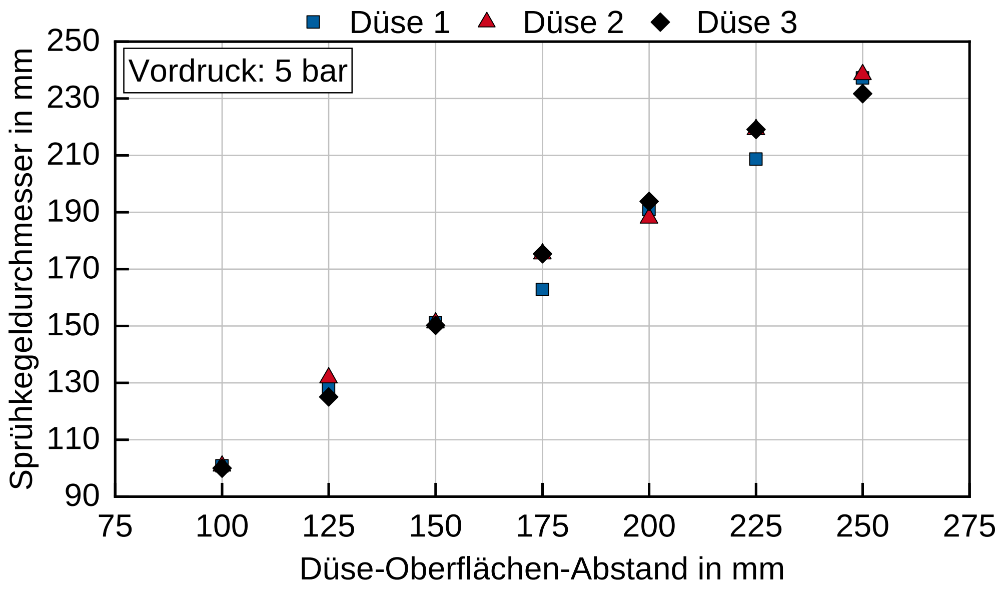
- Measurement of spray cone diameter possible
  - Influence of nozzle pressure and nozzle-surface-distance



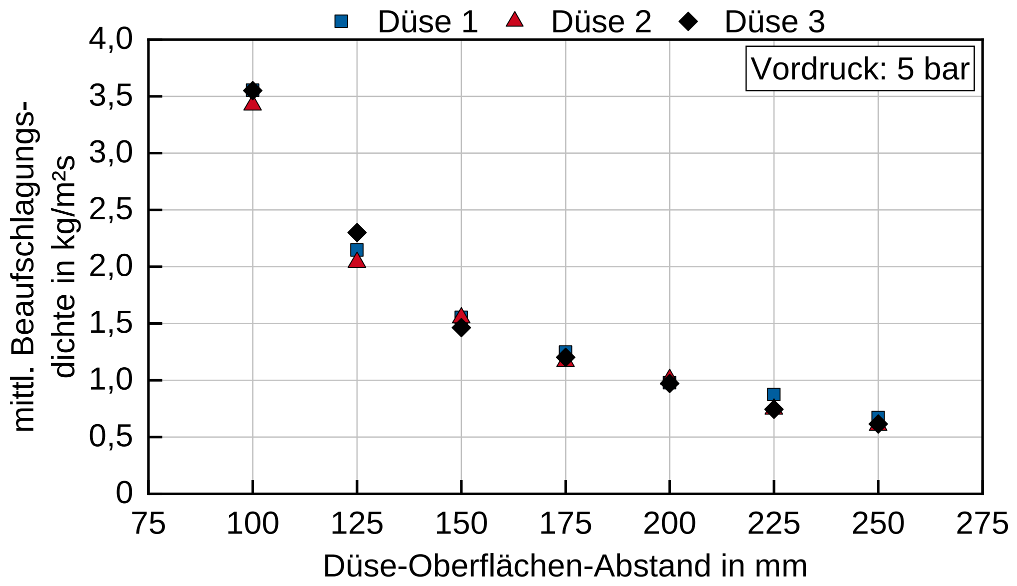
Flow on stationary surface

Single full cone nozzle

- Spray cone diameter at Patternator plane:
  - Linear increase with increasing nozzle-surface-distance
  - Nearly identical values for all investigated nozzles
  - Only slight increase with increasing nozzle pressure



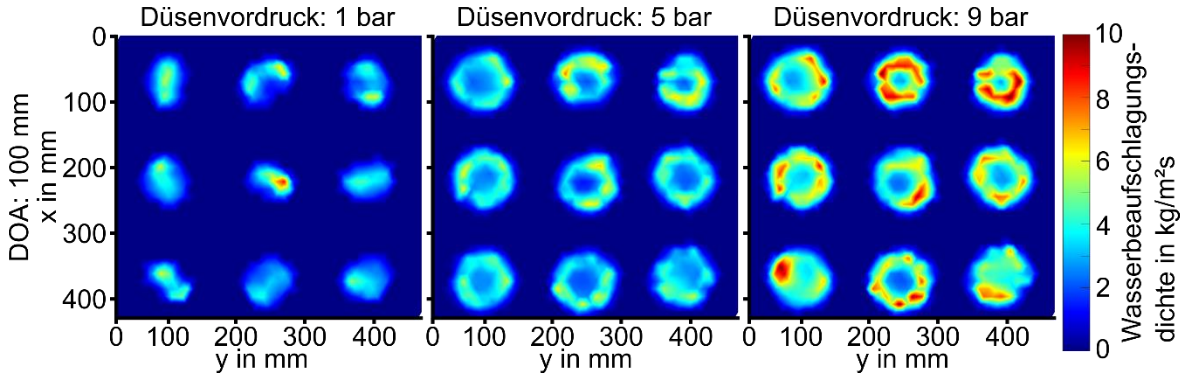
- Mean impingement density:
  - Asymptotic curve with nozzle-surface-distance
  - Theoretic maximum at orifice diameter
  - Theoretic minimum at infinite cone diameter
  - Nearly identical values for all investigated nozzles
  - Linear increase with increasing nozzle pressure



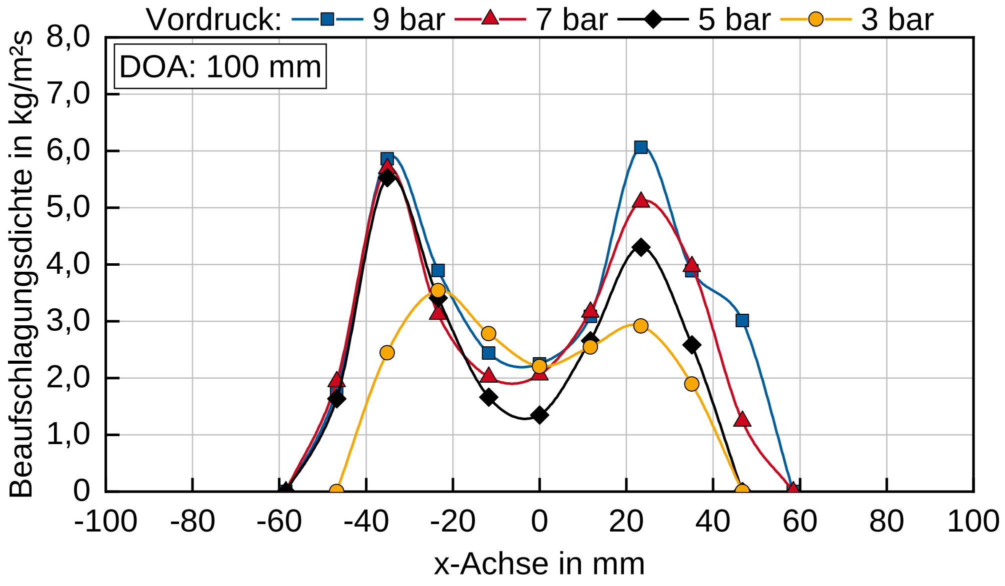
Flow on stationary surface

Nozzle field (3x3 aligned nozzle arrangement)

- Investigation with Patternator on nozzle fields
  - Impingement density measured
  - Nozzle-surface-distance: **H = 100 mm**
  - Nozzle-nozzle-distance: h = 150 mm
  - Varying nozzle pressures (p = 1 – 10 bar)



- Different spray behaviour with nozzle pressure
  - Developed spray pattern with p > 3 bar
  - Ring-shaped area at higher pressures

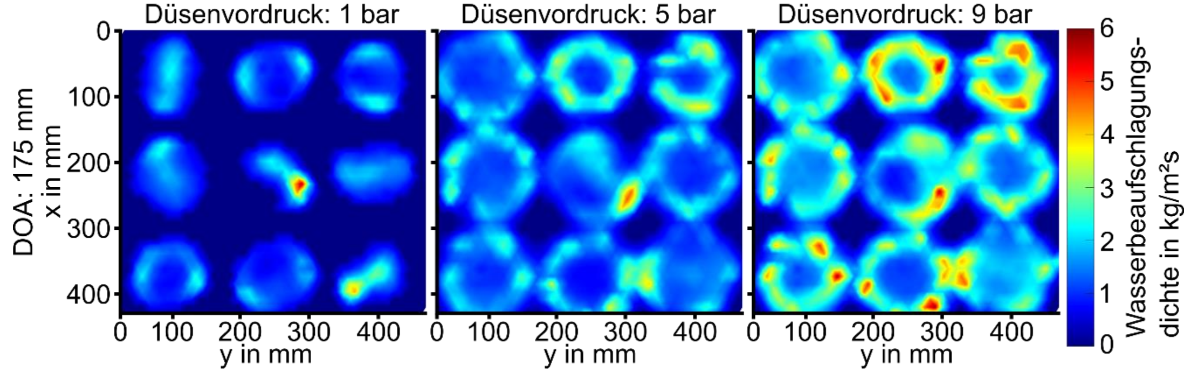


- No overlap between individual spray cones on the Patternator plane
  - Nozzles behave like single nozzles

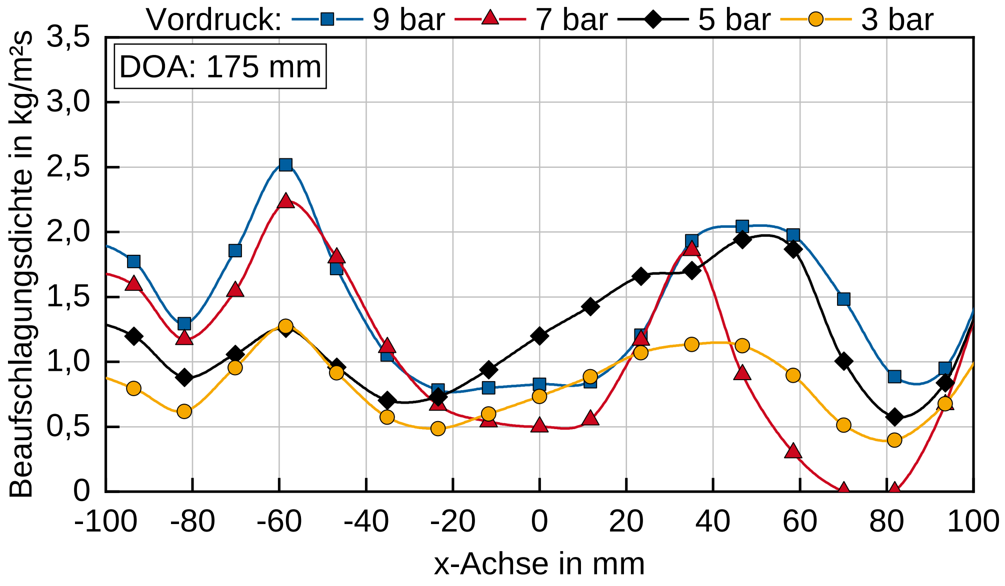
Flow on stationary surface

Nozzle field (3x3 aligned nozzle arrangement)

- Investigation with Patternator on nozzle fields
  - Impingement density measured
  - Nozzle-surface-distance: **H = 175 mm**
  - Nozzle-nozzle-distance: h = 150 mm
  - Varying nozzle pressures (p = 1 – 10 bar)



- Overlap between individual spray cones on the Patternator plane
  - Interaction between the sprays (peak height)
  - Increasing influence with increasing nozzle pressure
  - Only area between four nozzles without any impingement

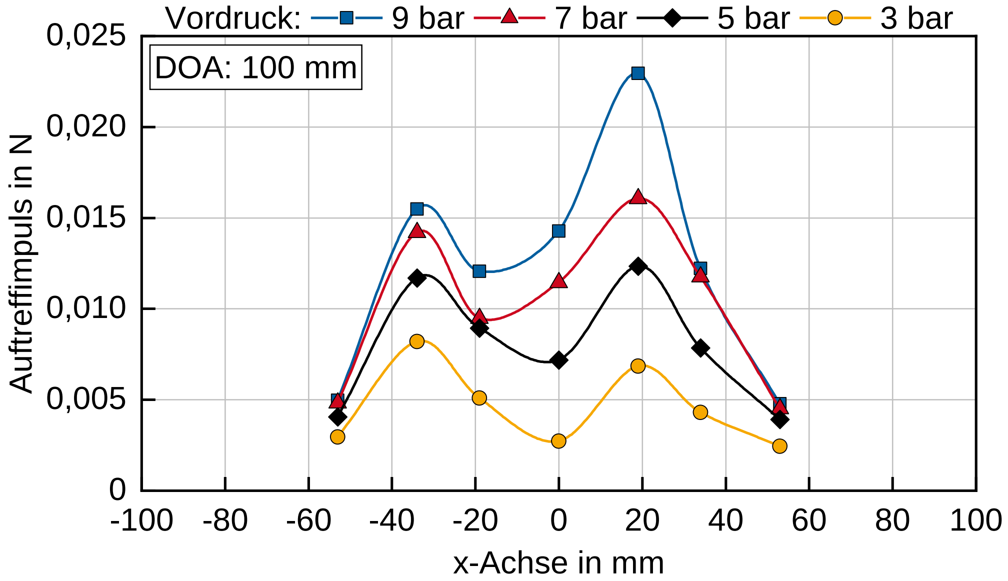


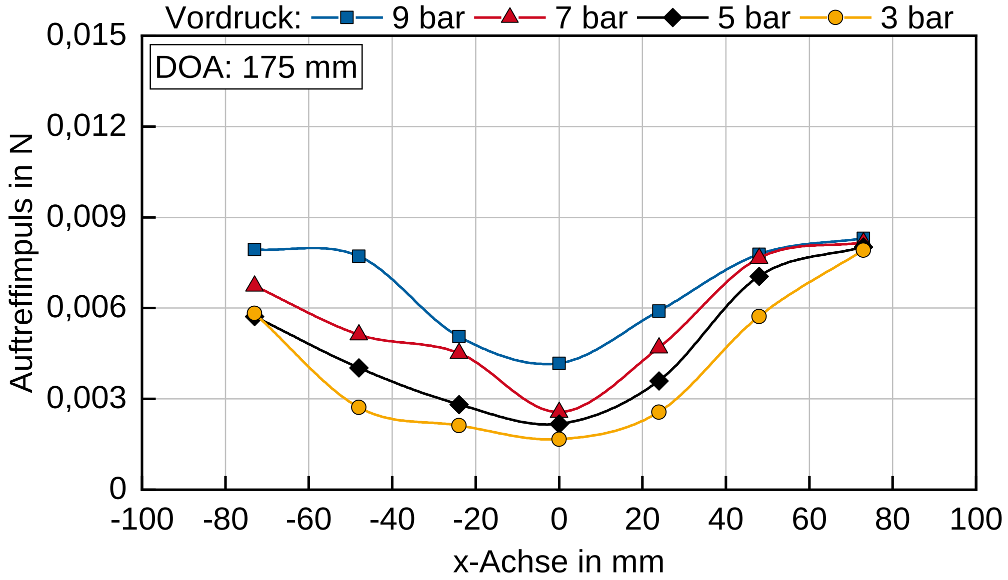
Flow on stationary surface

Nozzle field (3x3 aligned nozzle arrangement)

- Investigation with force sensor
  - Impact force measured along x-Axis
  - Nozzle-nozzle-distance: h = 150 mm
  - Varying Nozzle-surface-distance (H = 100 mm/175 mm)
  - Varying nozzle pressures (p = 1 – 10 bar)

- Different behaviour with nozzle to surface distance
  - Single nozzle behaviour at H = 100 mm
    - No interaction between individual sprays
    - Good correlation with impingement density
  - Nozzle field behaviour with increasing nozzle-surface-distance
    - No peaks visible
    - No direct correlation with impingement density
    - Water peaks obstruct direct impingement of the surface

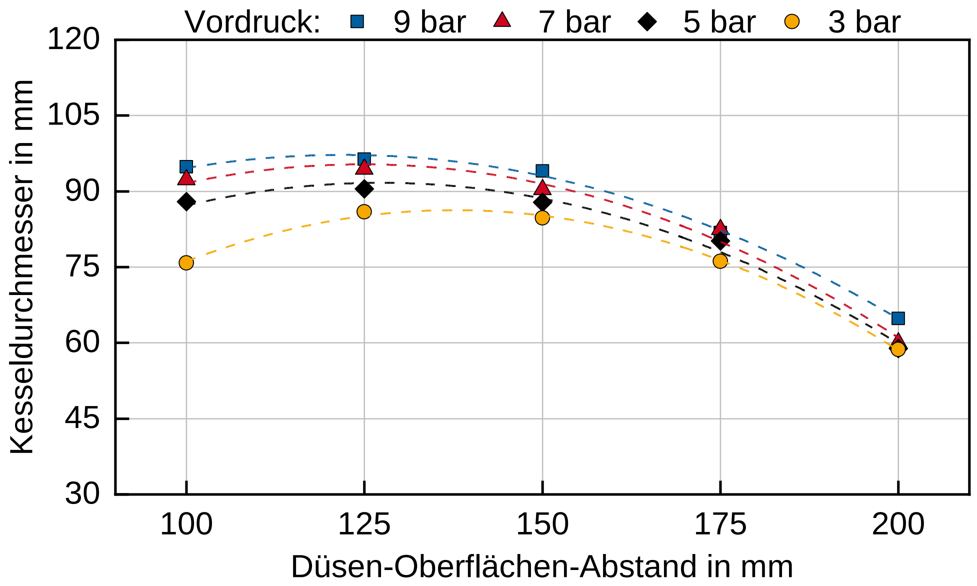




Flow on stationary surface

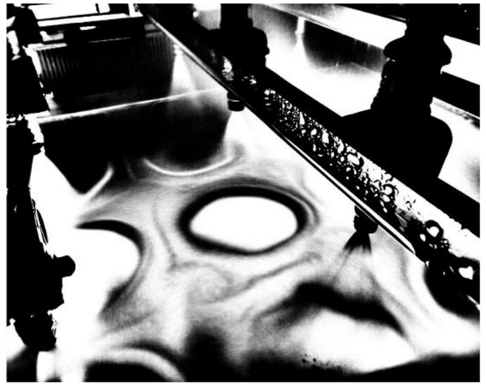
Nozzle field (3x3 aligned nozzle arrangement)

- Investigations with optical measurement method
  - Flow on the surface is investigated qualitatively and quantitatively
  - Varying Nozzle-surface-distance (H = 100 mm – 200 mm)
  - Varying nozzle pressures (p = 1 – 10 bar)
  - Nozzle-nozzle-distance: h = 150 mm



- Basin diameter decreases with increasing H
  - Formation of vortexes on the water peaks
  - Change of basin shape

DOA: 100 mm



DOA: 125 mm

DOA: 150 mm

DOA: 175 mm

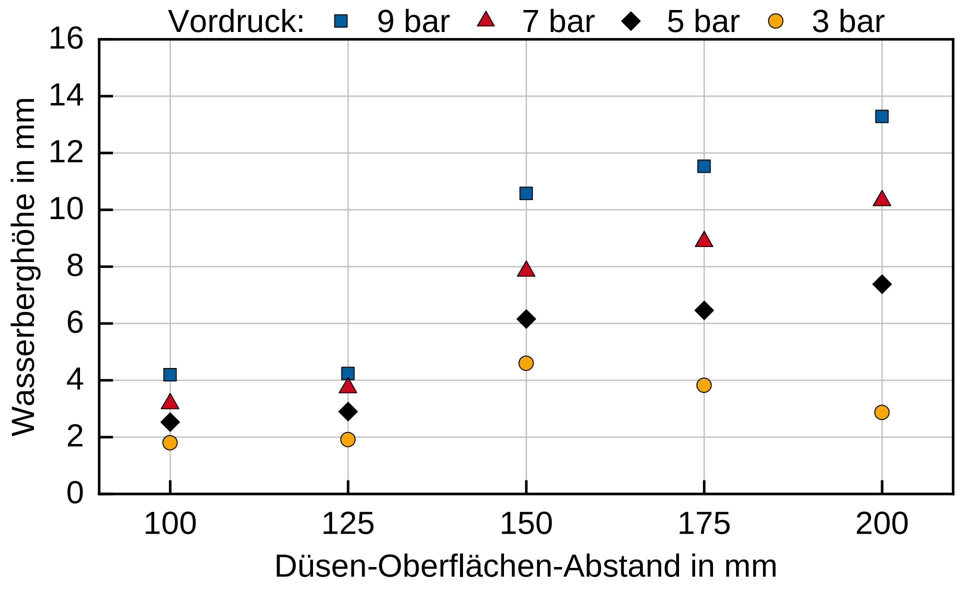
DOA: 200 mm

Flow on stationary surface

Nozzle field (3x3 aligned nozzle arrangement)

- Investigations with ultrasonic sensor
  - Measurement of the water peak height
  - Varying Nozzle-surface-distance (H = 100 mm – 200 mm)
  - Varying nozzle pressures (p = 1 – 10 bar)
  - Nozzle-nozzle-distance: h = 150 mm

- Increase in peak height as soon as threshold is passed
  - Roughly at starting point of “turbulent” flow as seen in the optical measurements
  - Increase with increasing nozzle-surface-distance
  - Exception: Investigations at nozzle pressure p = 3 bar
    - Spray pattern not fully developed at that point?

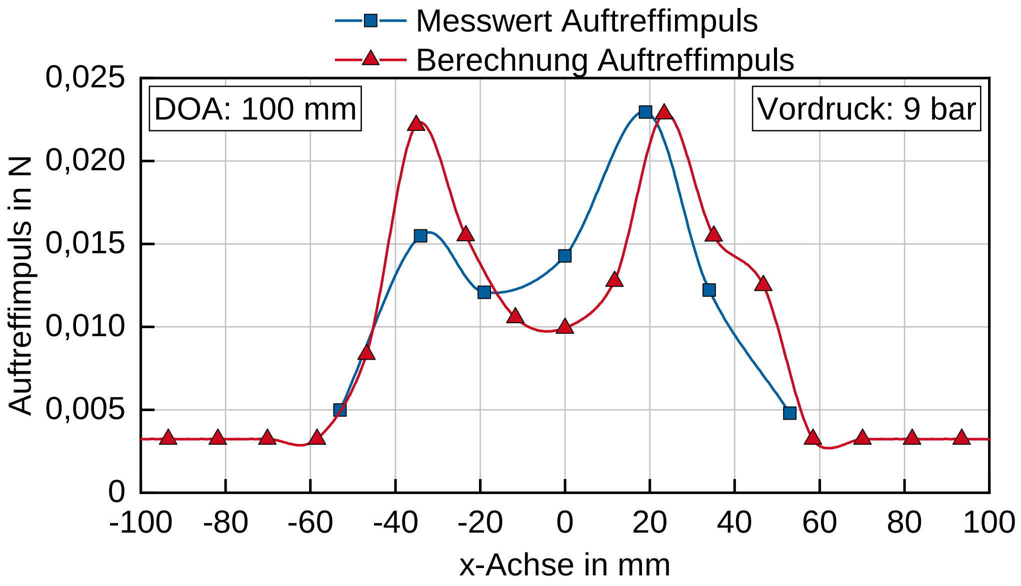


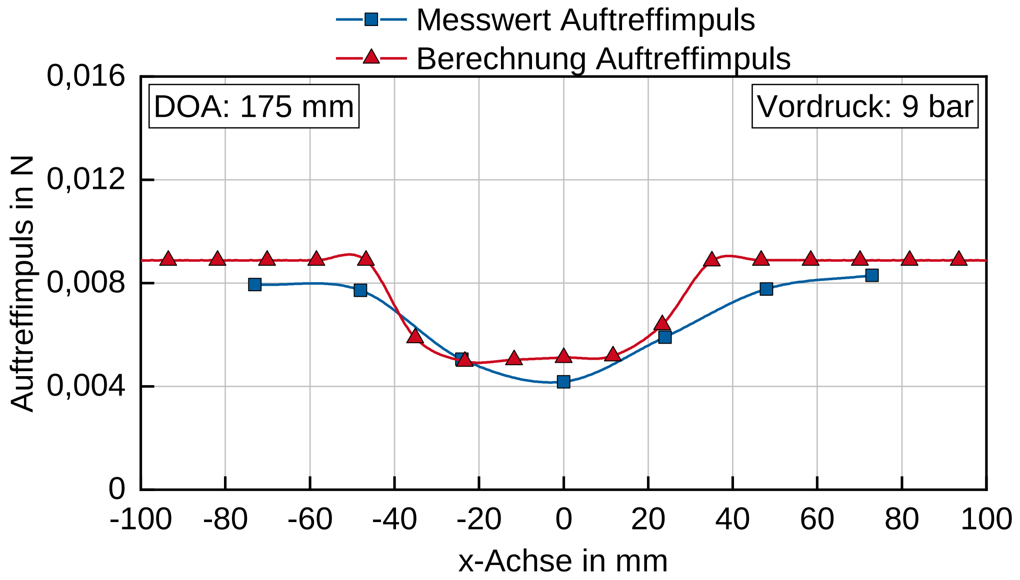
Flow on stationary surface

Nozzle field (3x3 aligned nozzle arrangement)

- Calculated and measured impact force in comparison
  - Impingement density as foundation for calculation
  - Adjustment with basin diameter
    - Inside basin: direct calculation from impingement density, imaginary sensor diameter and nozzle exit velocity
      $(\dot{I} = \dot{m}" \cdot A_{Sensor} \cdot u_{Düse})$
    - Outside basin: force from height of water peaks

- Good accordance for H = 100 mm as well as 175 mm
  - Single nozzle behaviour can be directly calculated
  - No direct impact below the water peaks measured, instead the height of the water peaks
    - Important for heat transfer
    - Inside basin: nozzle spray is decisive
    - Outside basin: flow beneath the peaks is decisive

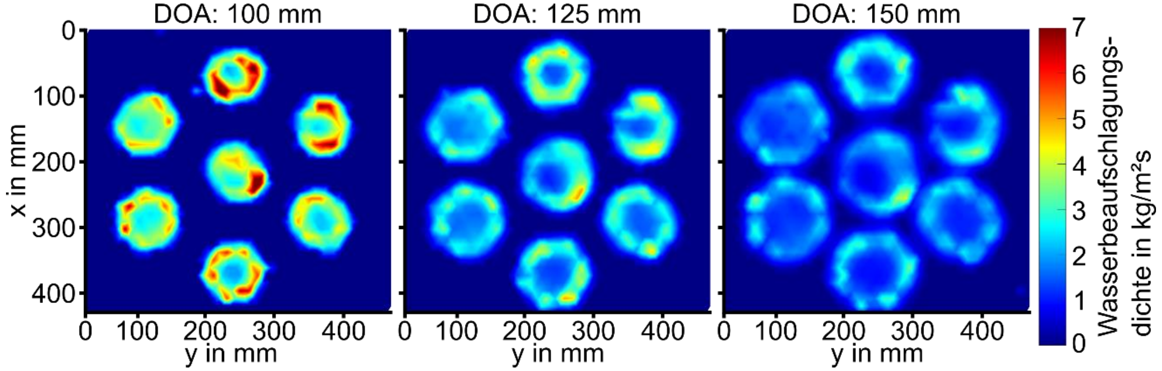




Flow on stationary surface (full cone nozzle field)

Nozzle field (3x3 staggered nozzle arrangement)

- Identical investigation with staggered nozzle arrangement
  - Varying Nozzle-surface-distance (H = 100 mm – 200 mm)
  - Varying nozzle pressures (p = 1 – 10 bar)
  - Nozzle-nozzle-distance: h = 150 mm



- Interaction between the nozzles starts at lower nozzle-surface-distances
  - Formation of vortexes at the water peaks
  - Change of basin shape

- Calculation of impact force
  - Determination of theoretical cooling rate with strip model

DOA: 100 mm DOA: 125 mm DOA: 150 mm

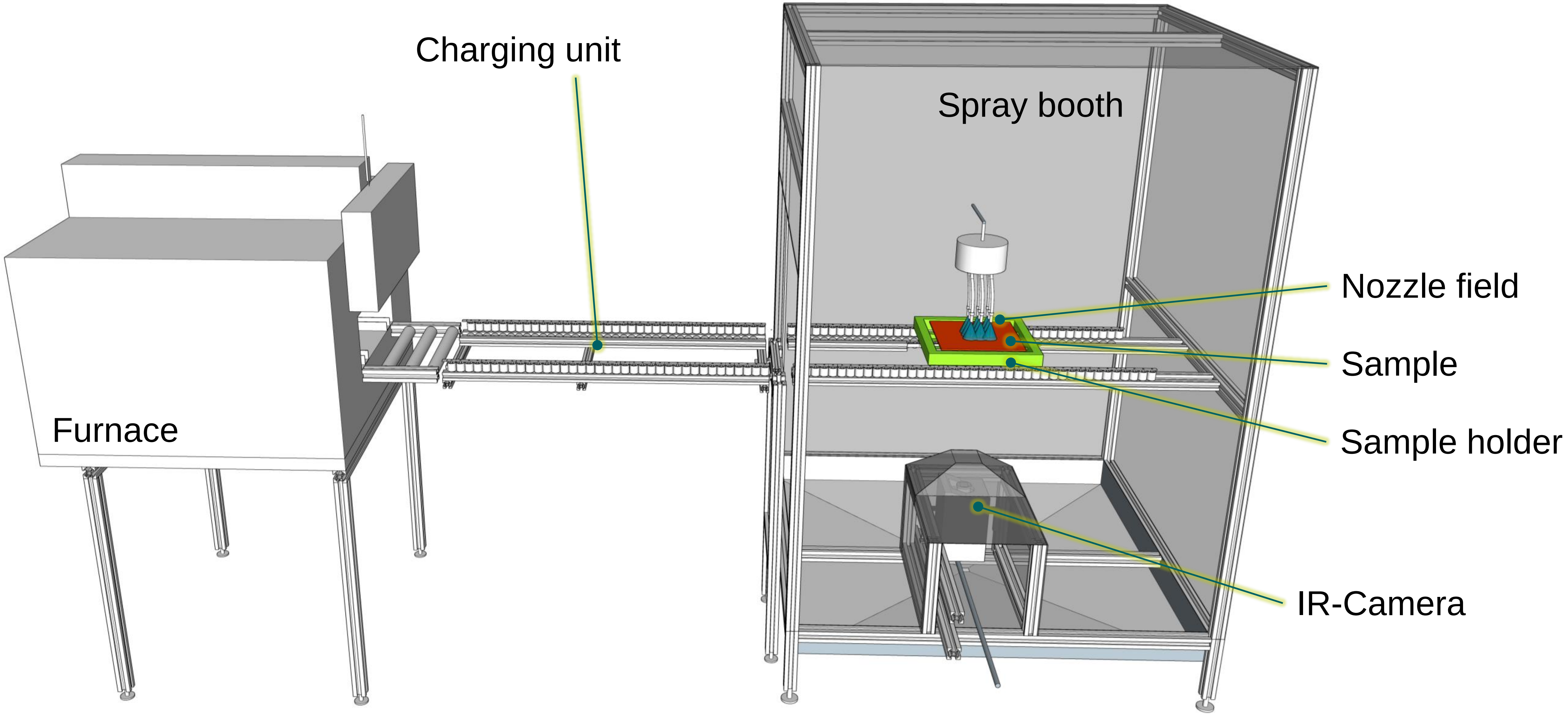
Test rig with circumferential strip (IOB)

- Additional test rig to investigate the influence of strip speed
  - Strip width currently 1 m
  - Strip speed up to 300 m/min
  - Circumferential strip
  - Strip centre measurement

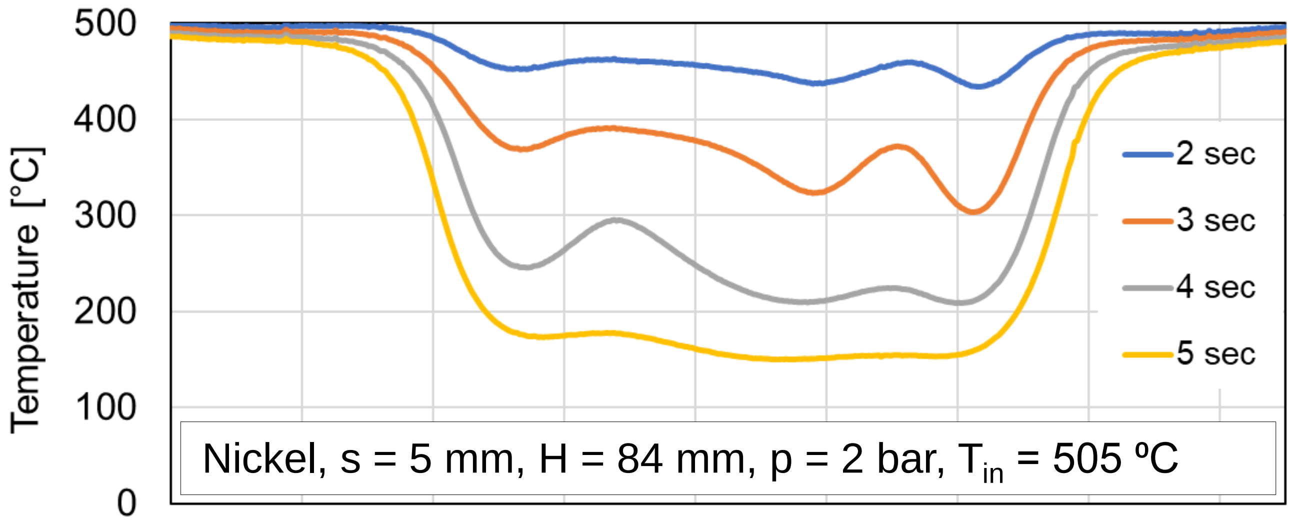
- Measurement options on the test rig
  - Optical measurement method
    - Dimensions of flow
  - Ultrasonic sensor
    - Water peak height

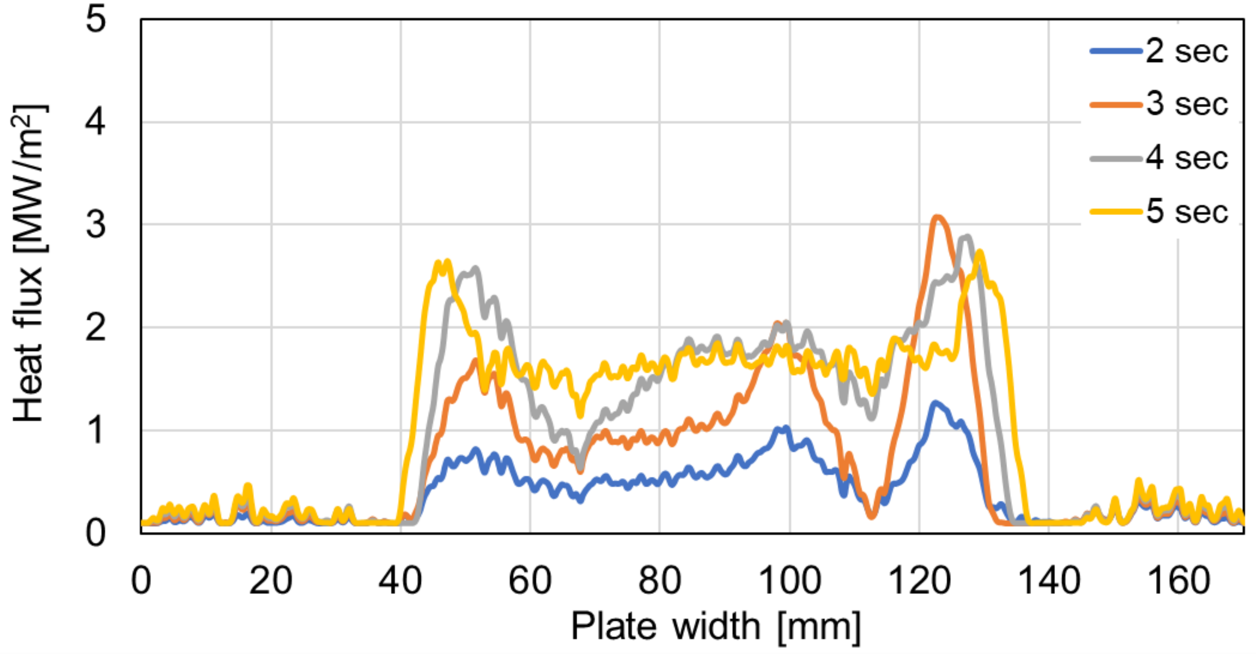
- Setup up is nearly finished
  - Measurements upcoming

Test rig for determining the heat transfer (LTV)

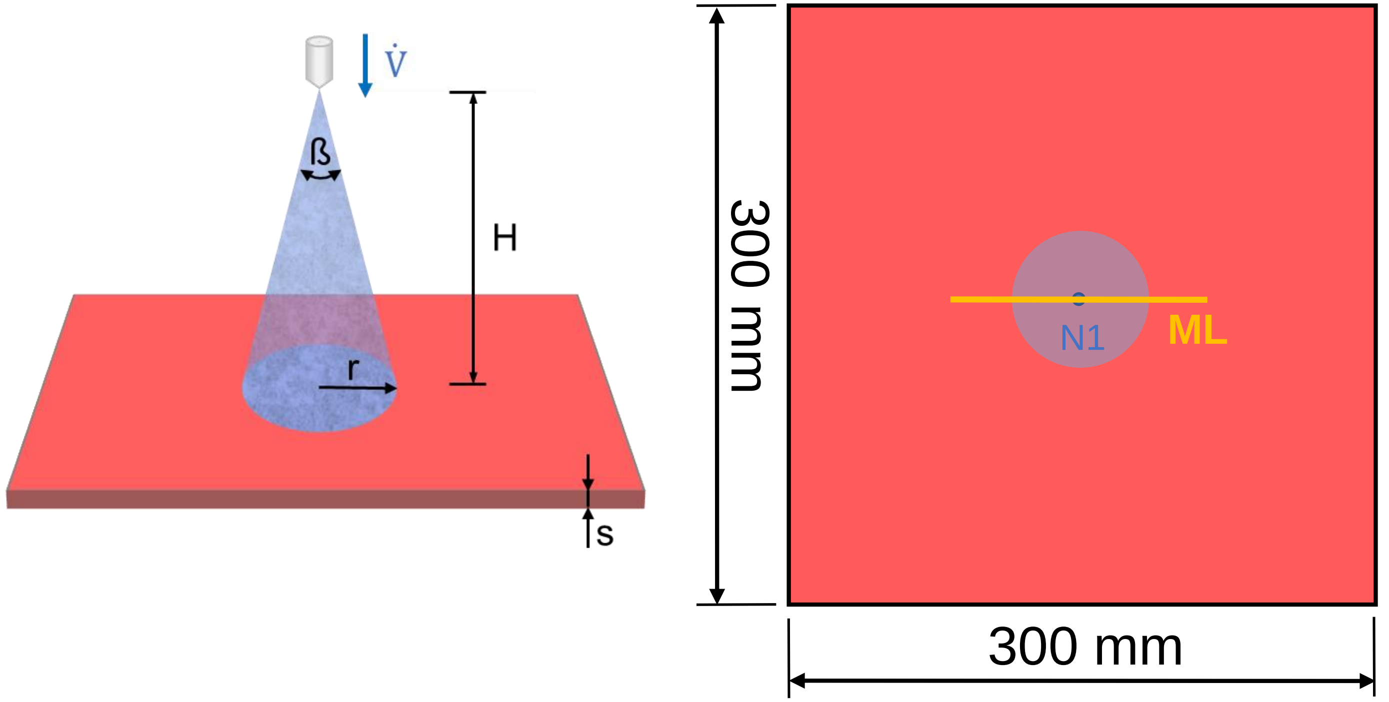


Heat transfer on stationary sheets (Nickel, s = 5 mm)





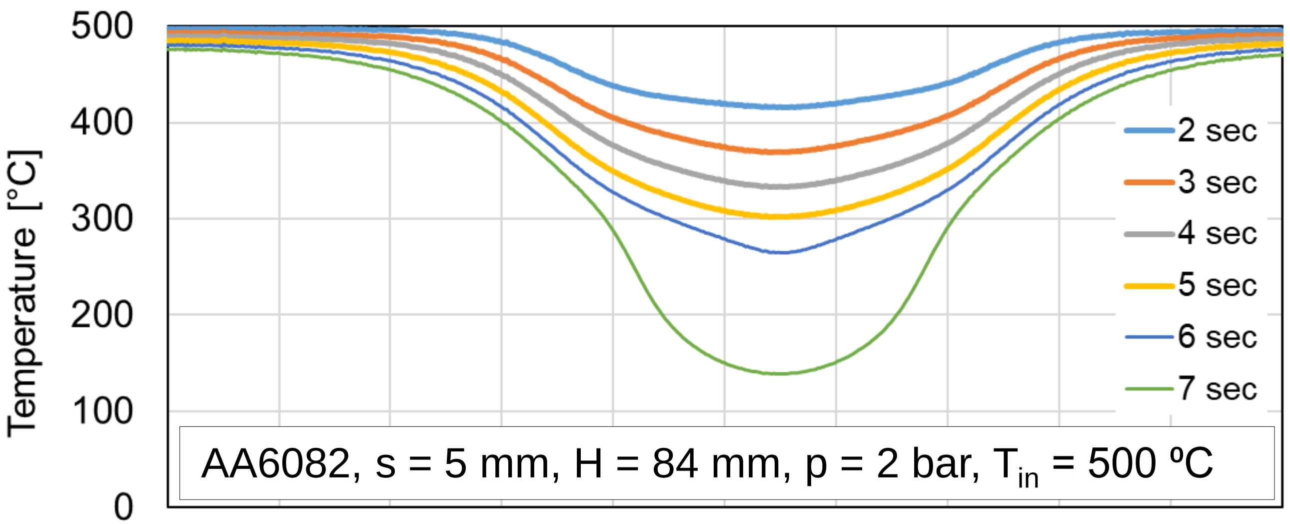
Single full cone nozzle

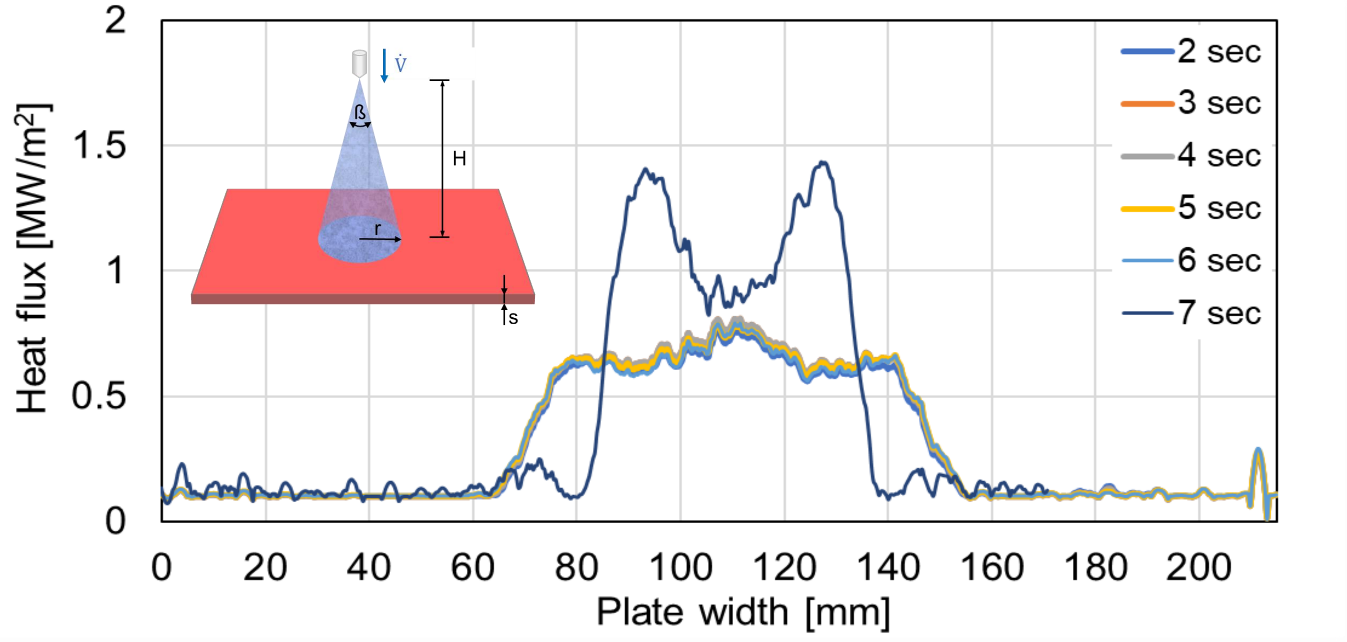


p = 2 bar ($V_{Düse}$ = 2 L/min)

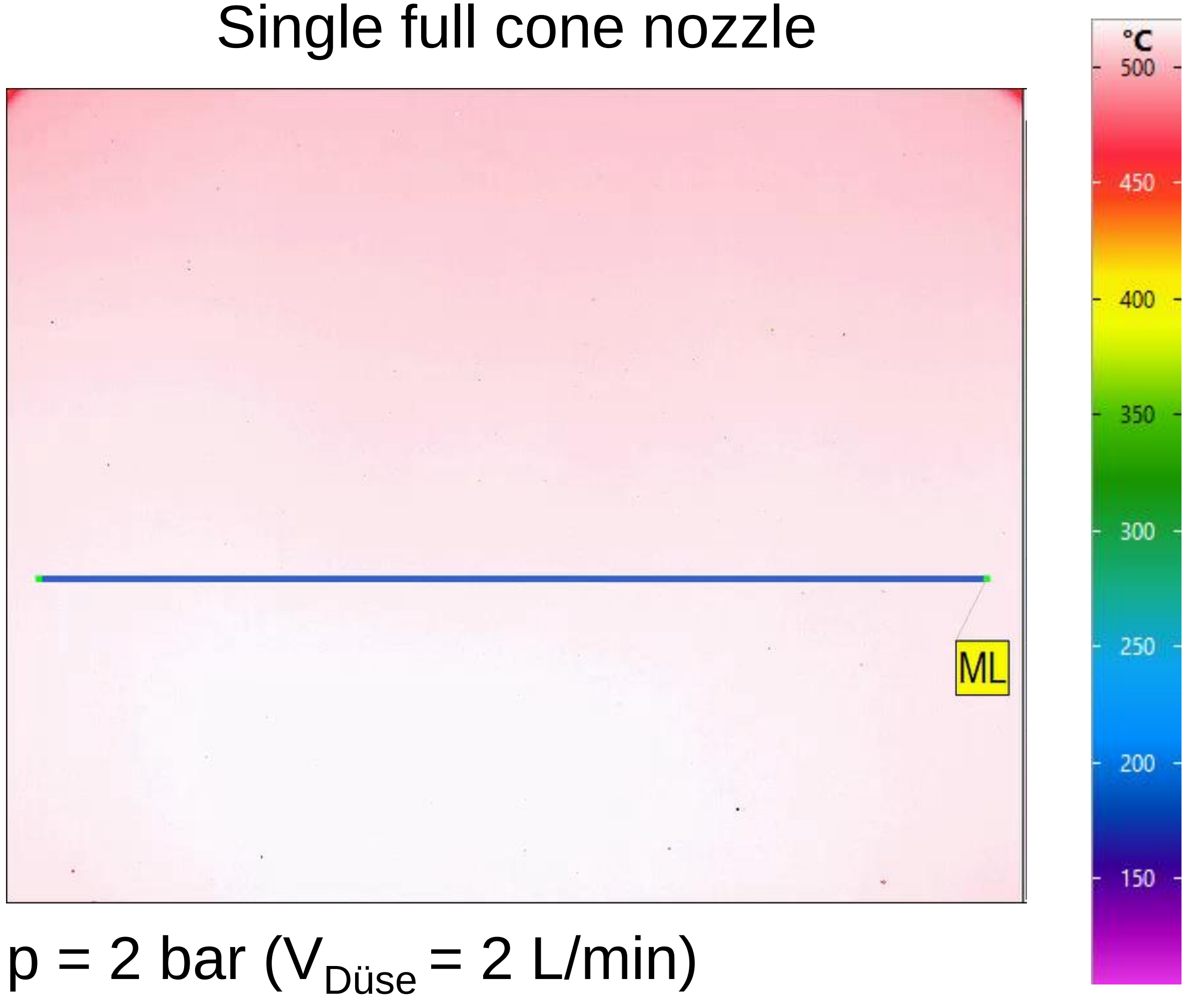
H = Distance nozzle - sheet

Heat transfer on stationary sheets (AA6082, s = 5 mm)





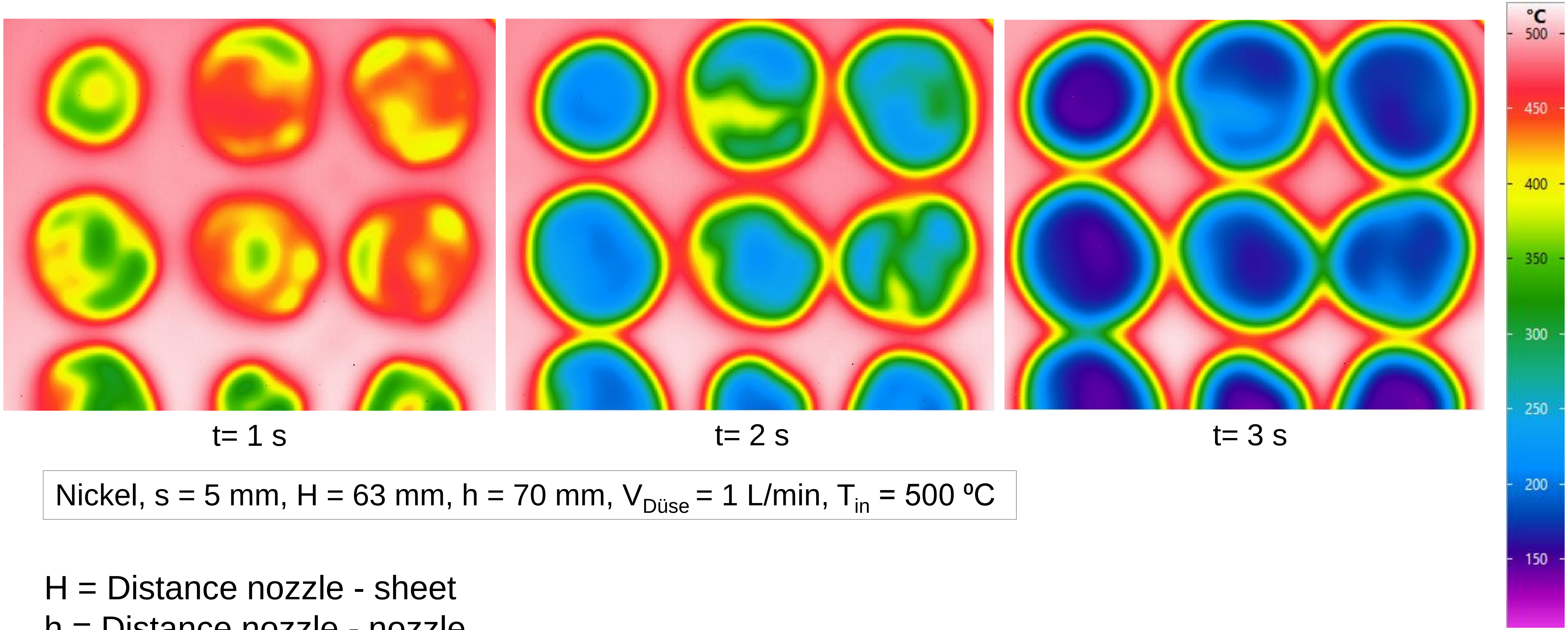
Single full cone nozzle



p = 2 bar ($V_{Düse}$ = 2 L/min)

H = Distance nozzle - sheet

Heat transfer on stationary sheets in nozzle field (9 x full cone nozzles)

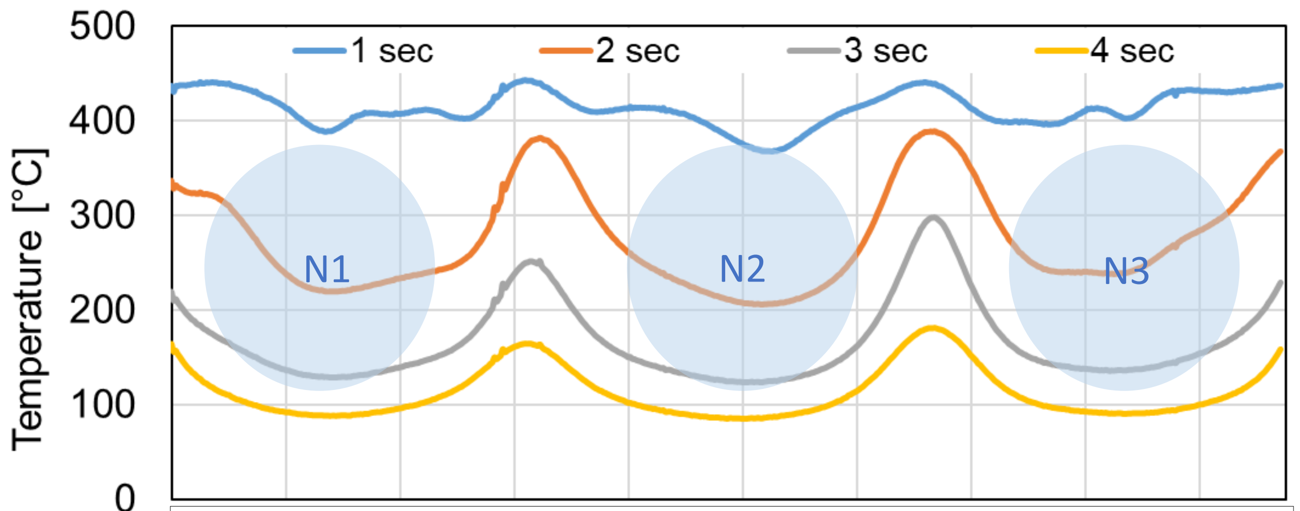


t= 1 s   t= 2 s   t= 3 s

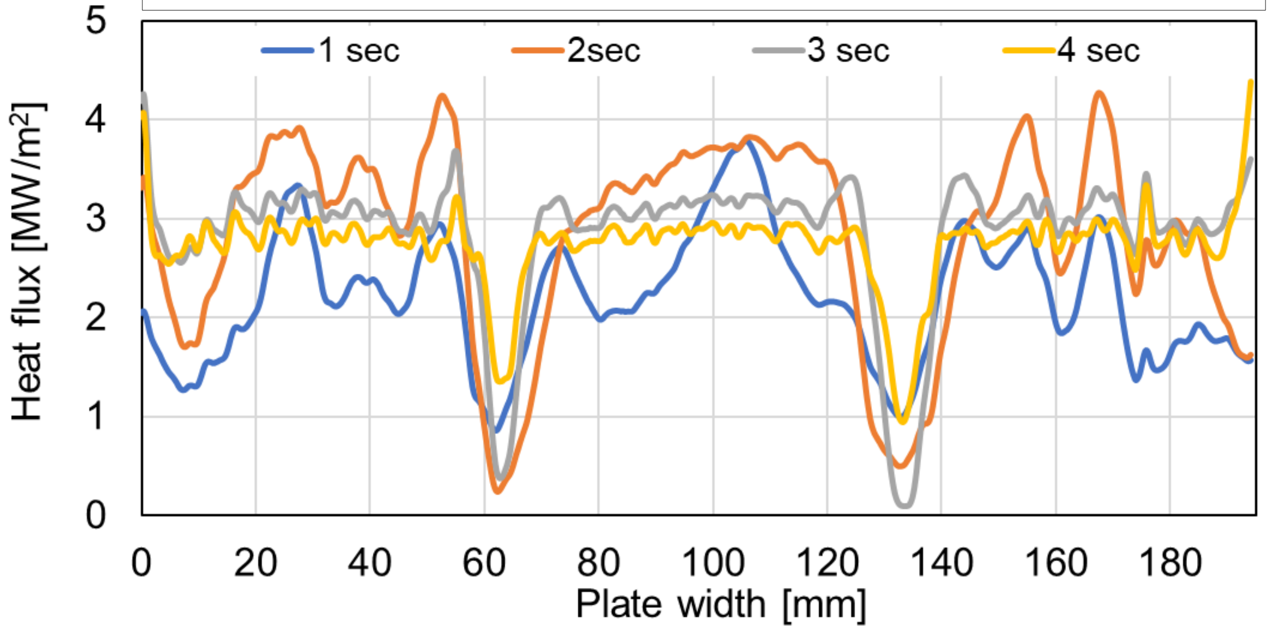
Nickel, s = 5 mm, H = 63 mm, h = 70 mm, $V_{Düse}$ = 1 L/min, T_{in} = 500 ºC

H = Distance nozzle - sheet
h = Distance nozzle - nozzle

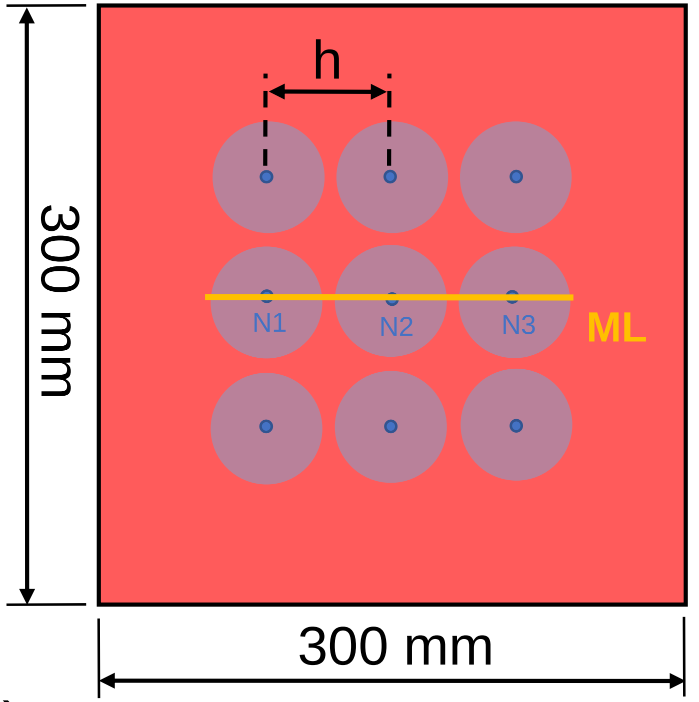
Heat transfer on stationary sheets (Nickel, s = 5 mm)



Nickel, s= 5 mm, H= 63 mm, h= 70 mm, p= 2 bar, T_{in} = 500 ºC



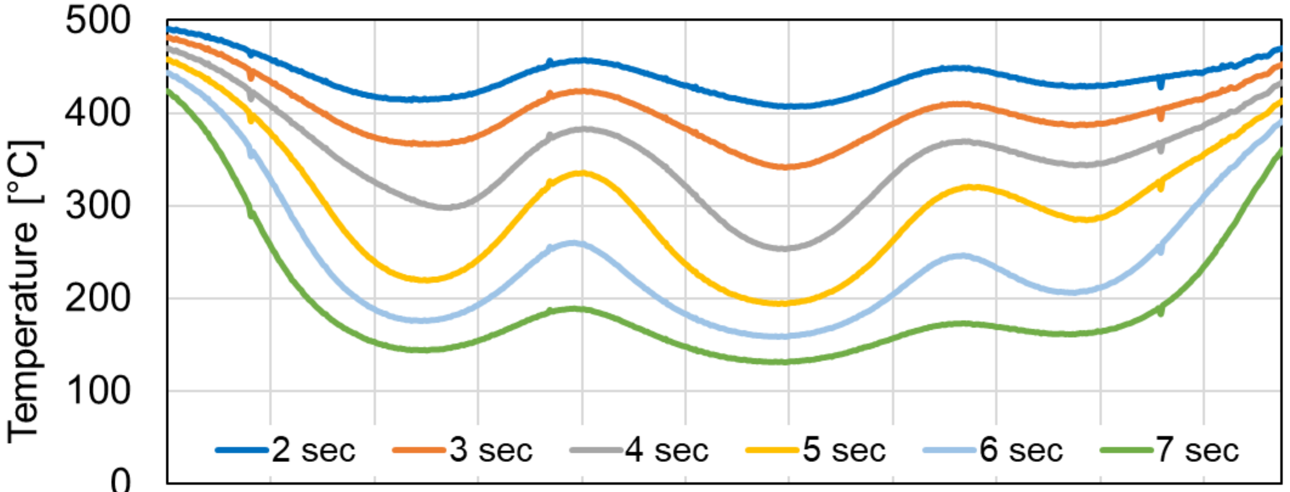
Nozzle field (9x full cone nozzles)



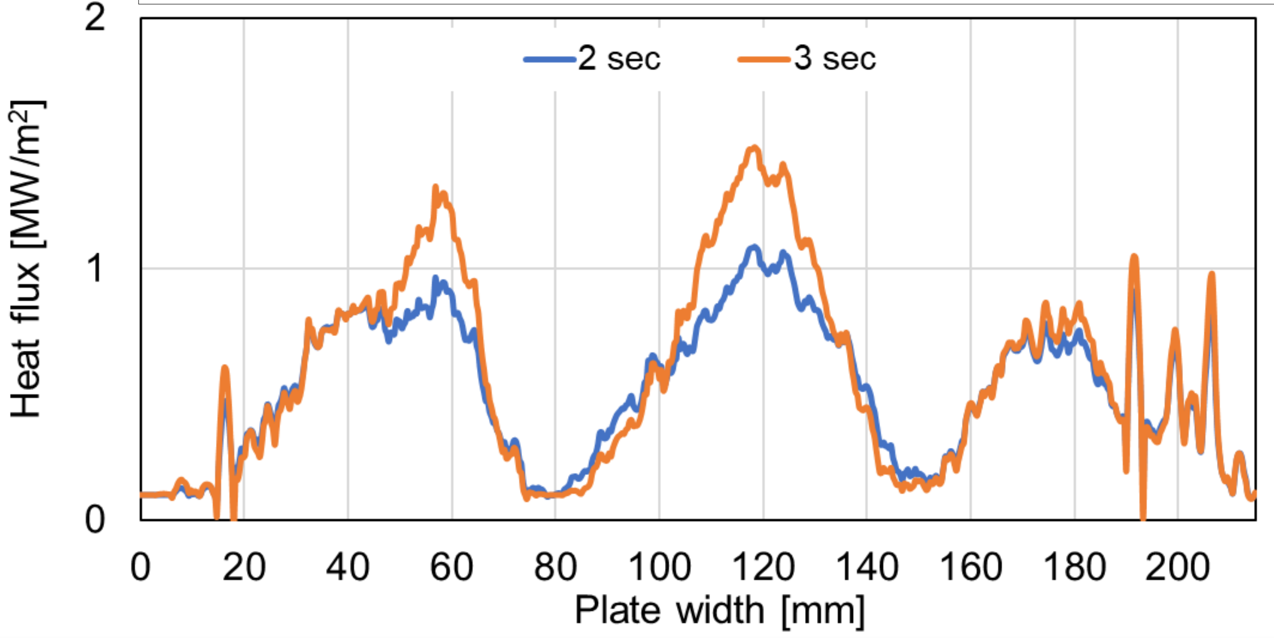
p = 2 bar ($V_{Düse}$ = 2 L/min)

H = Distance nozzle - sheet
h = Distance nozzle - nozzle

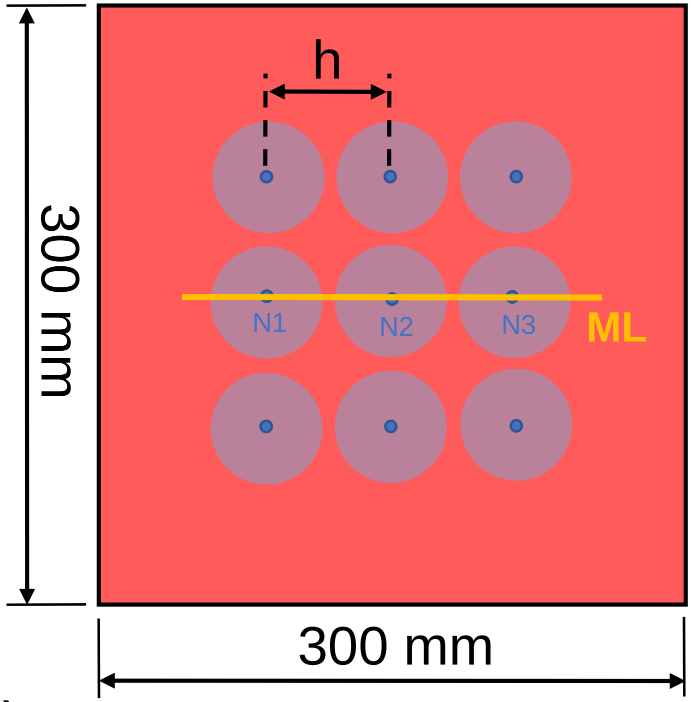
Heat transfer on stationary sheets (AA6082, s = 10 mm)



AA6082, s = 10 mm, H = 63 mm, h = 70 mm, p = 2 bar, T_{in}= 500 ºC



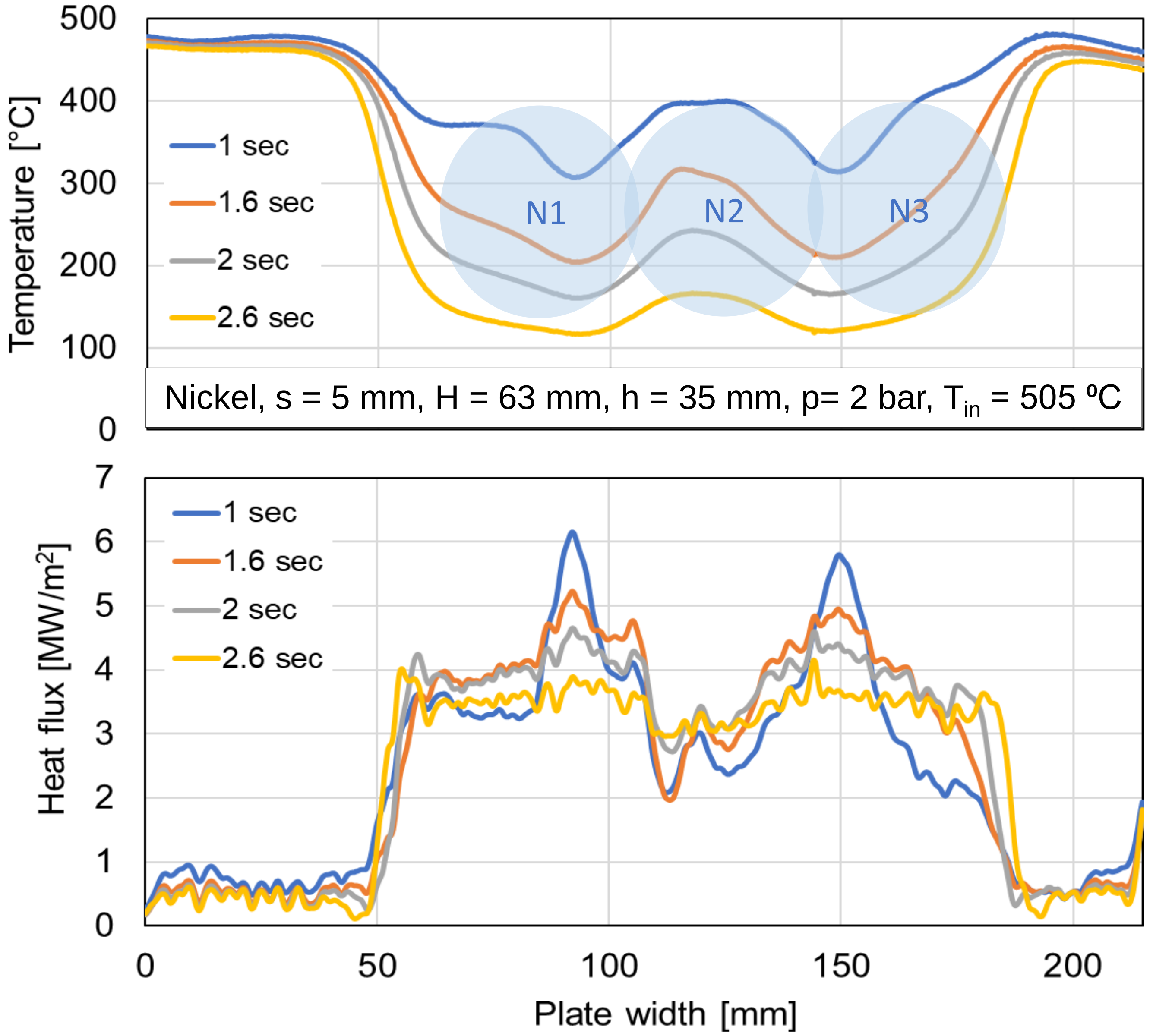
Nozzle field (9x full cone nozzles)



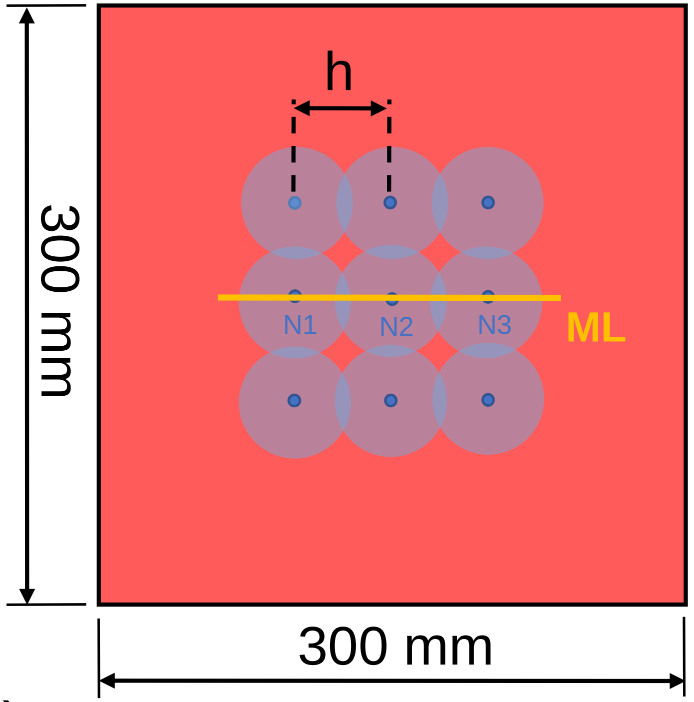
p = 2 bar ($V_{Düse}$ = 2 L/min)

H = Distance nozzle - sheet
h = Distance nozzle - nozzle

Heat transfer on stationary sheets (Nickel, s = 5 mm)



Nozzle field (9x full cone nozzles)

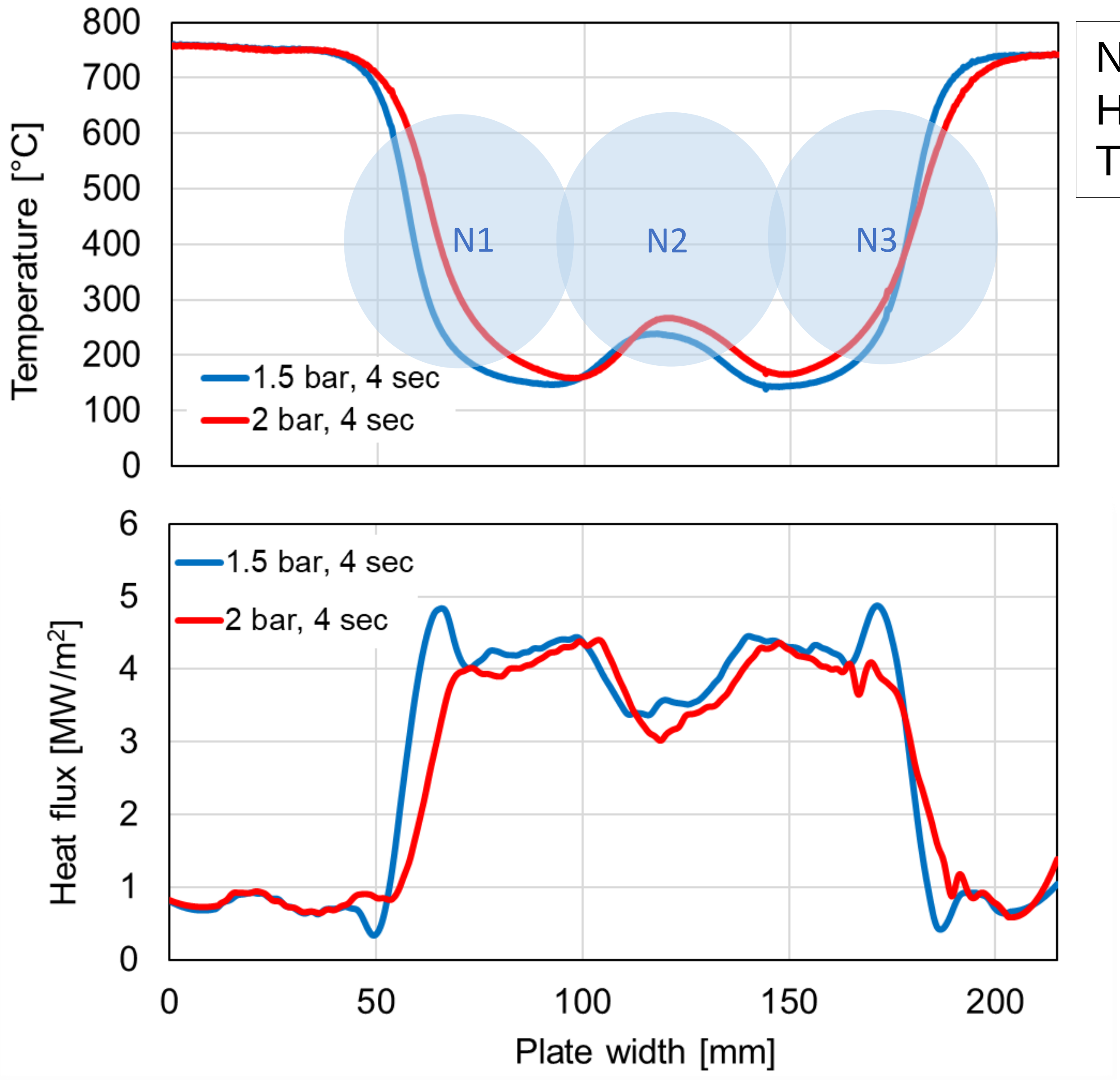


p = 2 bar ($V_{Düse}$ = 2 L/min)

H = Distance nozzle - sheet

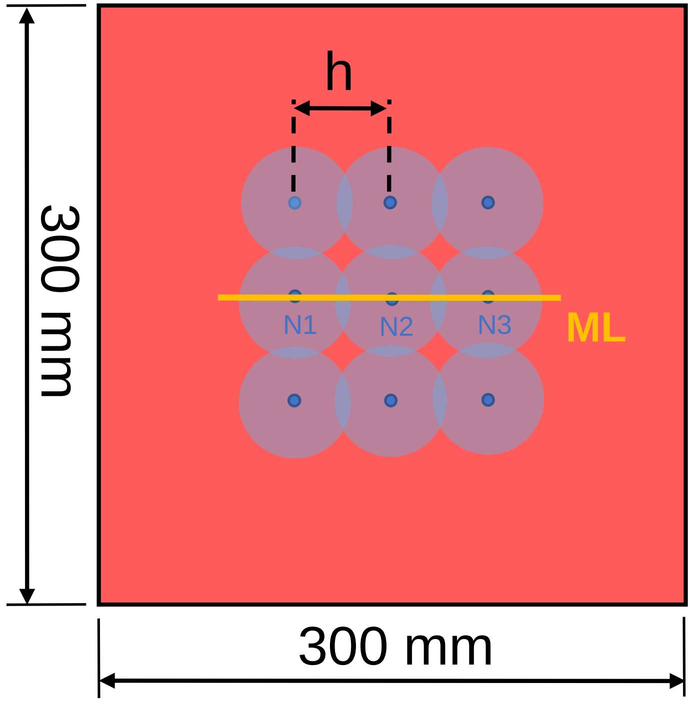
h = Distance nozzle - nozzle

Heat transfer on stationary sheets



Nickel, s = 5 mm,
H = 63 mm, h = 35 mm,
T_{in} = 800 ºC, t = 4 s

Nozzle field (9x full cone nozzles)



Flow on stationary surface (full cone nozzle field)

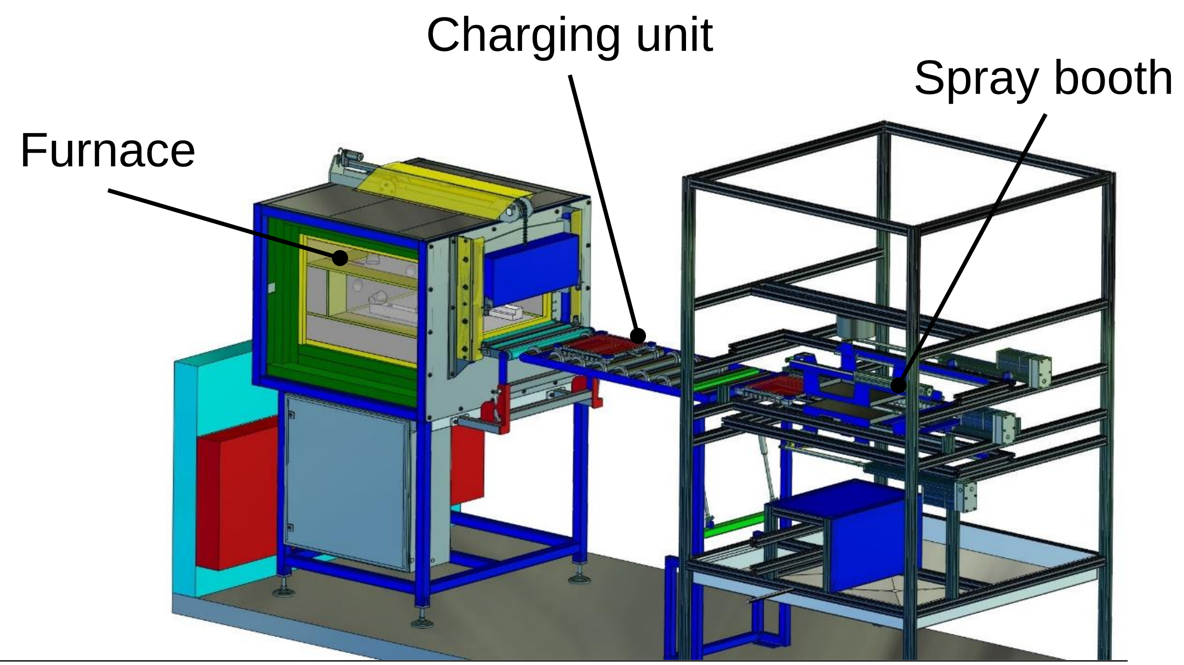
Initial findings:

- Single nozzle - inhomogeneous heat transfer within the spray cone area
  – HTC larger in the peripheral area than in the centre

- Nozzle field - high cooling capacity in the centre (no contact between spray cones)
  – Low cooling capacity in the centre (overlapping spray cones) - water mountains?

Further investigations:

- Experiments with moving sheet
- Comparison between stationary and moving sheet
- Comparison of HTC in and across moving direction
- Experiments with higher nozzle pressures



Spray nozzle fields

Summary

- Investigations of flow
  - Measurement of impingement density, flow behaviour, impact force and peak height
  - Single nozzles and nozzles fields investigated
  - Wide range for relevant parameters covered (nozzle pressure, nozzle-surface-distance, nozzle-nozzle-distance)
  - Influence of strip speed coming up

- Investigations of heat transfer
  - Experiments on stationary sheets with varying parameters in nozzle fields
  - Investigations on moving sheets coming up

- Delay and extension due to Corona-Virus

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Thinking the Future
Zukunft denken

Industrielle
Gemeinschaftsforschung

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OTTO VON GUERICKE UNIVERSITÄT MAGDEBURG

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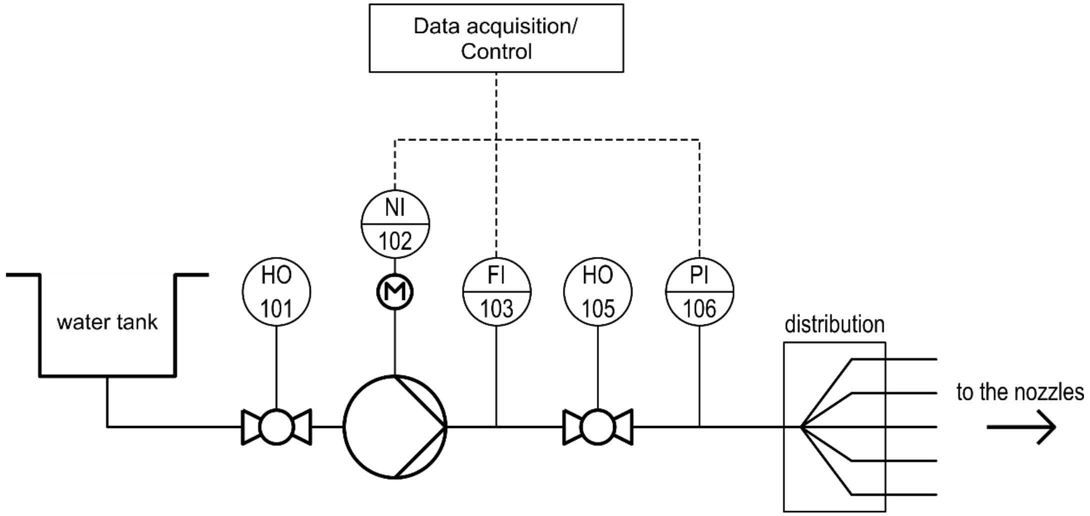
RWTH AACHEN UNIVERSITY

Flow on a non-moving horizontal surface

- Test rig with spray nozzle field
  - Individual nozzle type or nozzle size
  - Variable number of nozzles (currently 3x3)
  - Nozzle field size up to 400 x 400 mm²
  - Variable distances between the nozzles (currently: 35 - 400 mm)
  - Variable distance between the nozzles and the surface (currently: 0 - 250 mm)
  - Nozzle inlet pressure (currently: 1 - 12 bar)

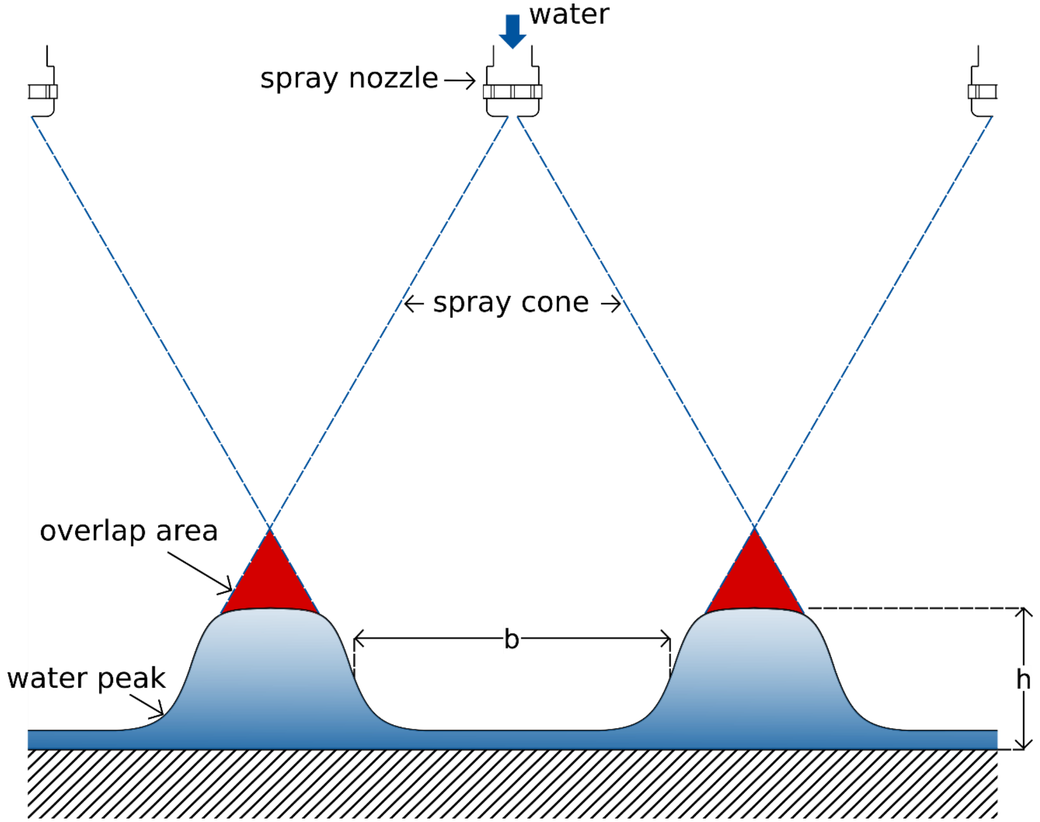
- Acrylic glass as horizontal plate

- Measurement options on the test rig
  - Optical measurement method
    - Dimensions of flow
  - Patternator
    - Impingement density
  - Force sensor
    - Impact of Spray

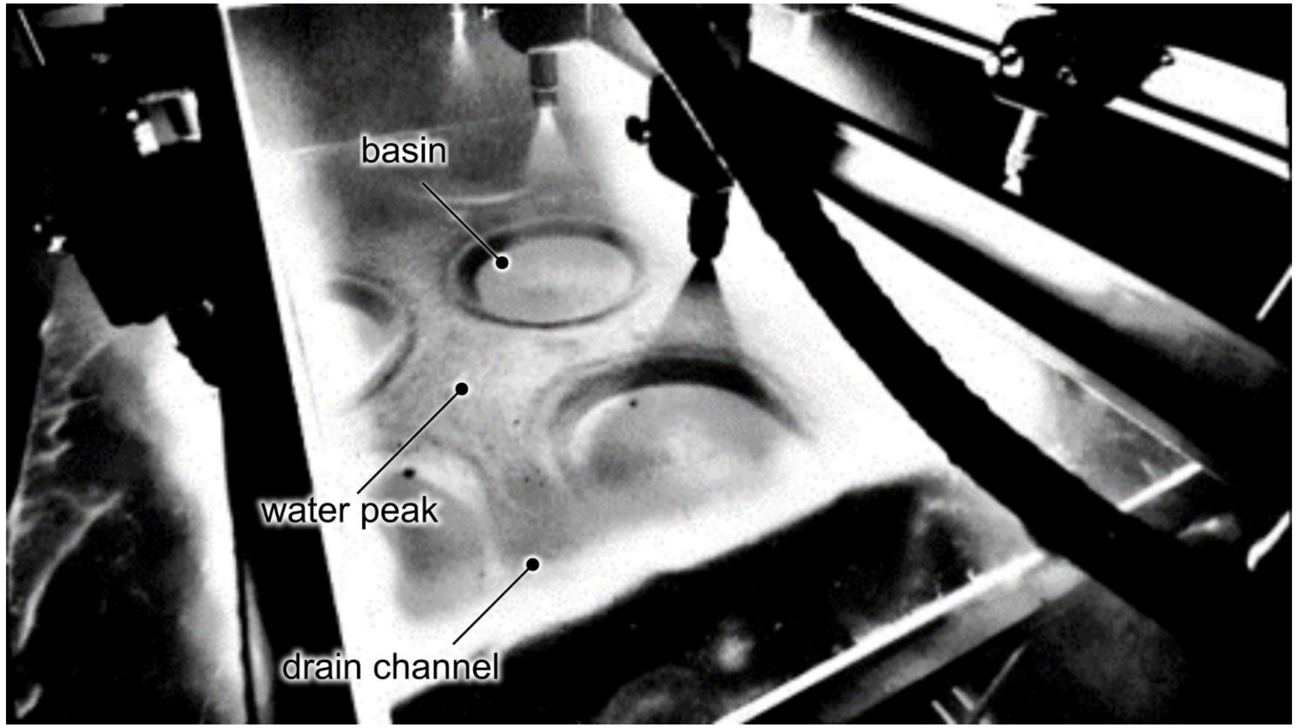


Flow on a non-moving horizontal surface

- Quantification of characteristics on the strip surface for flow determination:
  - Stagnation points, "water peaks"
  - Impact region, "basin“
  - Runoff water, drain channels



- Influence on the local cooling rate and temperature homogeneity
- Determination of influencing factors
  - Nozzle inlet pressure
  - Nozzle spacing
  - etc.



Development of the optical measurement method

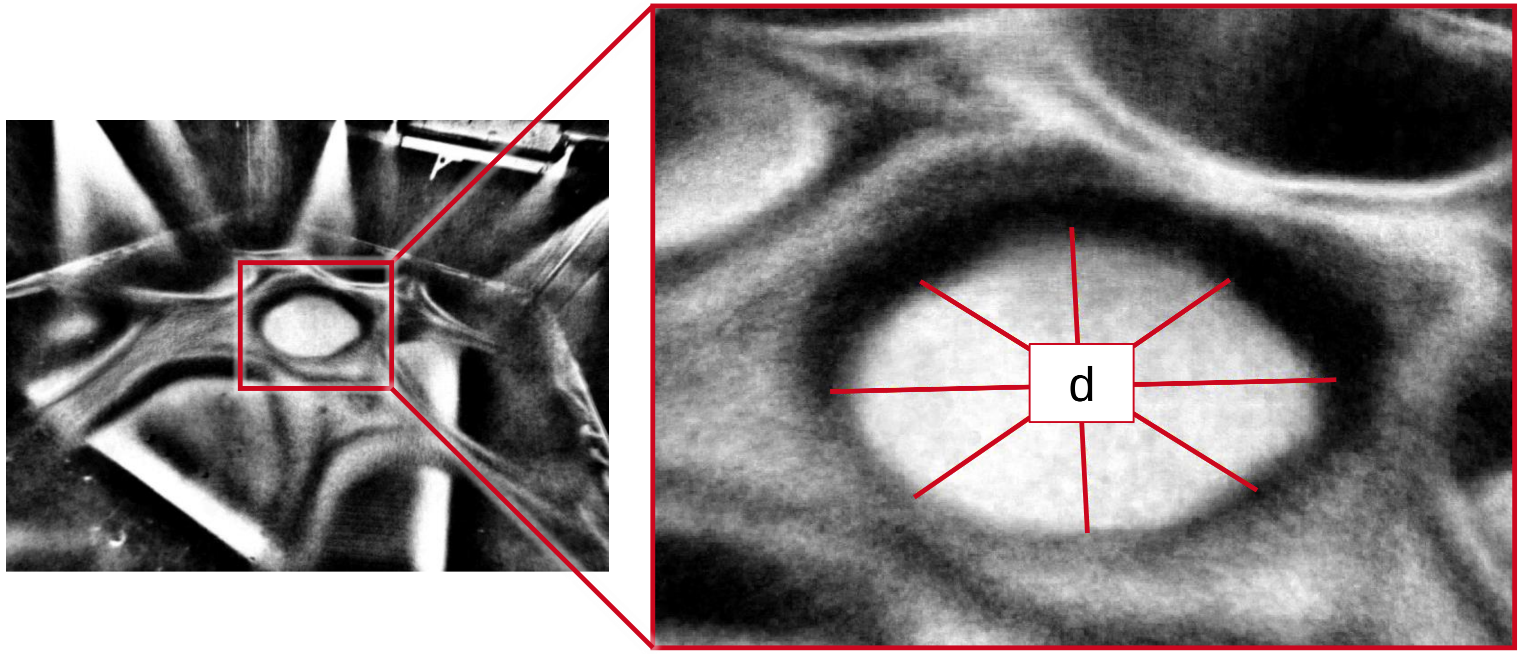
1. Acquisitions with cameras
   - Compact design
   - Flexible positioning
   - Low acquisition costs

2. Camera calibration and distortion correction
   - Calibration to correct distance
   - MATLAB-Toolbox

3. Grayscale image or black/white image
   - Enhanced contrasts
   - Interfaces can be recognized more easily
   - Dependent on lighting direction

4. Superimposition of images
   - Time averaging of flow phenomena
   - Enhanced contrasts
   - Qualitative analysis already possible

5. Measurement of basin diameter
   - 4 measurement points per image
   - Averaging over multiple camera positions and complete trail duration
   - Quantitative analysis of the flow



Patternator

- Measuring principle
  – Ultrasonic sensor and 2D traverse
  – Distance between sensor and water surface
- 1330 measuring points
  – 38 x 35 rows, staggered
  – 465 x 440 mm²
- Automatic evaluation of each tube
  – Measuring time for Patternator currently ~ 35 min
- Calculation of 2D impingement density
  – Determination of impact-area (diameter)
  – Average over area