Testing of Diagnostic Systems for Measuring Particle Properties in Cold Spray

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Outline

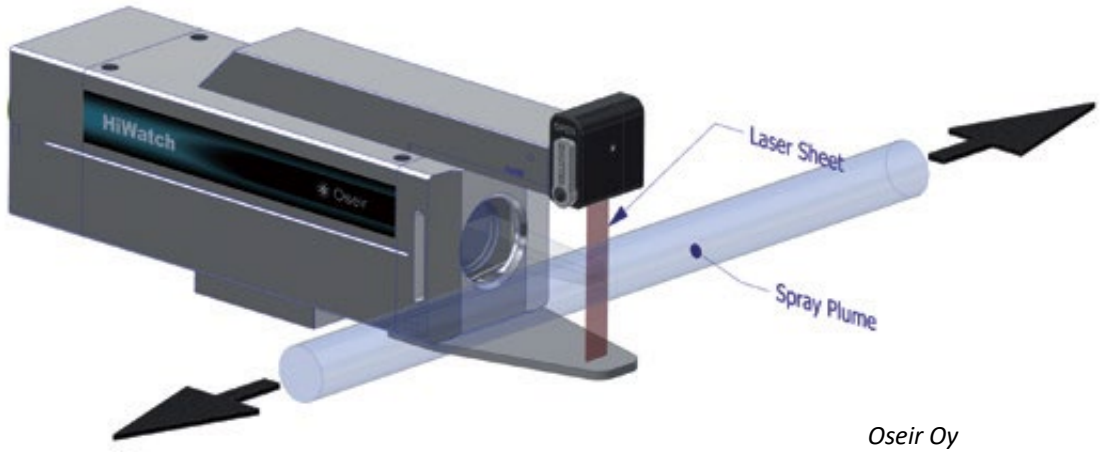
Testing of Diagnostic Systems for Measuring Particle Properties in Cold Spray

- Tests with HiWatch CS2 and Horiba
  - Fine Powder
- Tests with HiWatch HR2, CSM, and Horiba
  - Fine Powder
  - Coarse Powder
- Conclusions

Measuring Particle Position, Velocity, and Size

Particle tracking velocimetry (PTV) by Oseir HiWatch CS2

Measurement principle	**Scattered light from a laser sheet**
Measurement area	≈ 8 mm lateral x 6 mm axial
Measurement depth	≈ 1 mm
Particle velocity range	0 – 2000 m/s
Particle diameter range	5 – 1000 µm
Capture speed	> 10 fps
Camera resolution	1920 x 1200
Laser wavelength	≈ 800 nm



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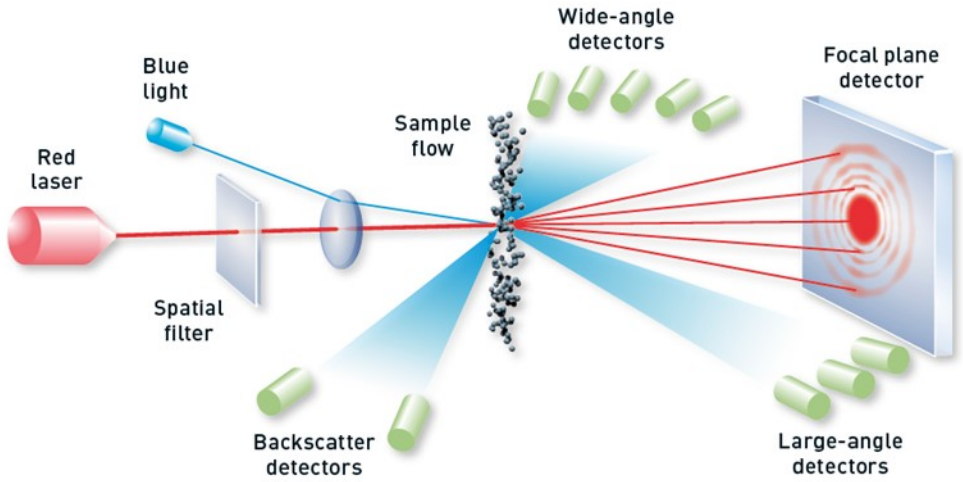
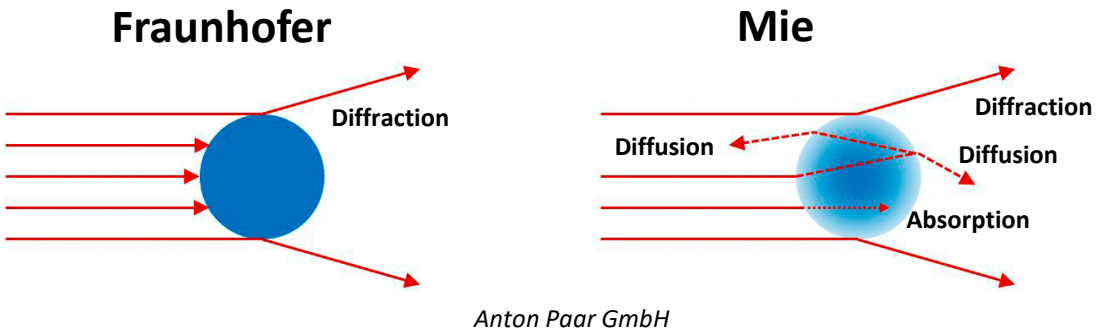
Measuring Particle Size

Horiba LA-950

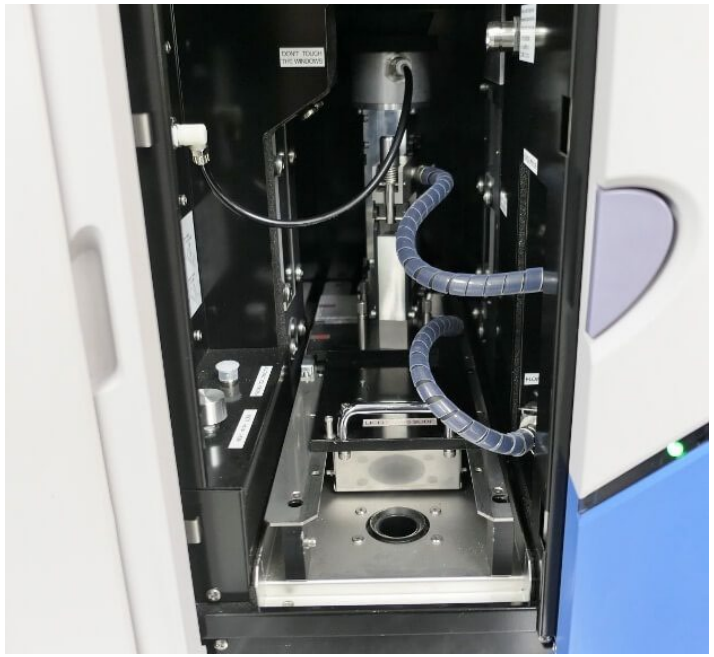


Malvern Panalytical Ltd

Measurement principle	**Laser diffraction**
Measurement range	0.01 – 3.000 µm
Accuracy	± 0.6% of NIST standard
Precision	± 0.1% coeff. of var. of NIST standard
Capture speed	5000 scans/s
Evaluation approach	Fraunhofer, Mie scattering
Laser wavelength	650 nm Laser diode 5.0 mW 405 nm light emitting diode 3.0 mW



Anton Paar GmbH



Horiba GmbH

Investigated Cases with HiWatch CS2 and Horiba

Cold Spray System Impact 5/11, N_2 , 4.0 MPa, 950°C, Spray Distance 60 mm

IN 718 **fine** powder (BCM 395 M): Oerlikon Metco AE 10718, -22 / +5 µm

d_{10} = 9.6 µm

d_{50} = 14.2 µm

d_{90} = 19.6 µm

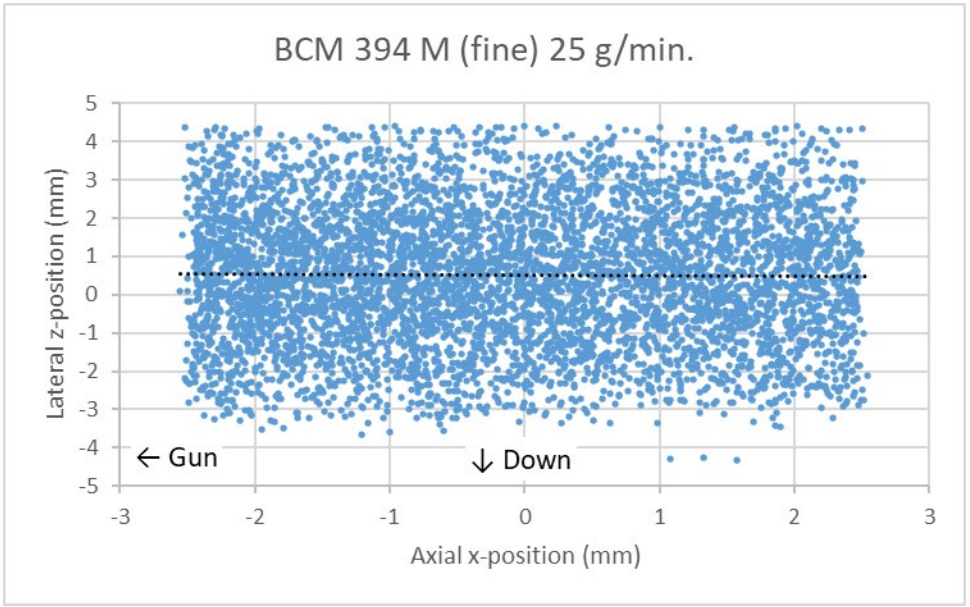
Feed rates 6.3, 12.5, and 25.0 g/min

Particle size distribution by laser diffraction

Results: HiWatch CS2

Local Particle Distribution, 25 g/min. Fine Powder

- 5723 particles
- Center of measured particle distribution approx. 0.5 mm above torch axis
- Particle density evenly distributed over the measurement field.



Comparison: HiWatch CS2 - Horiba

Particle Diameters, 6 – 25 g/min. Fine Powder

HiWatch CS2

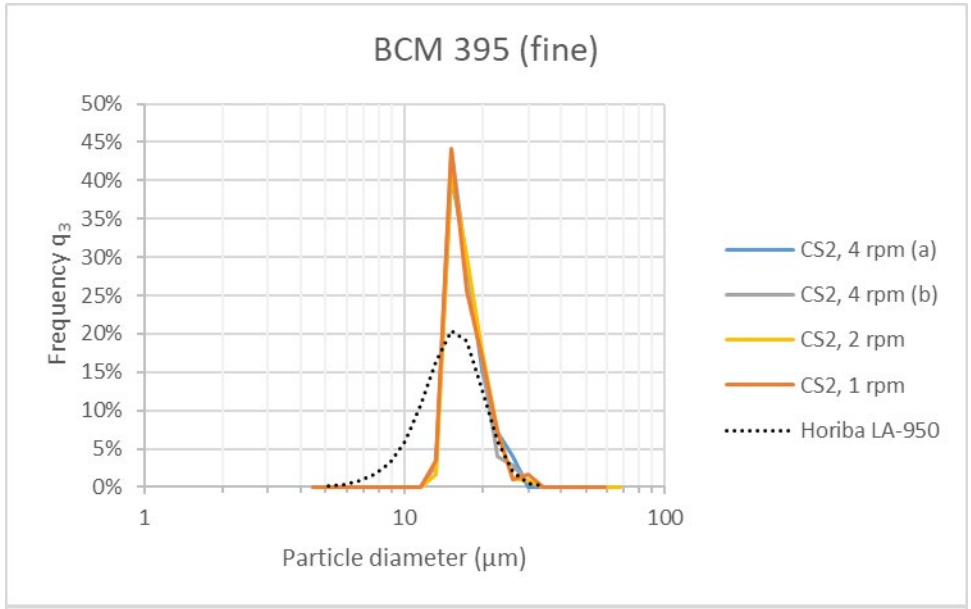
- Sizing is not biased by powder feed rate.
- Shape of density distribution is cut at lower detection limit Ø ≈ 12.5 µm.
- Good repeatability

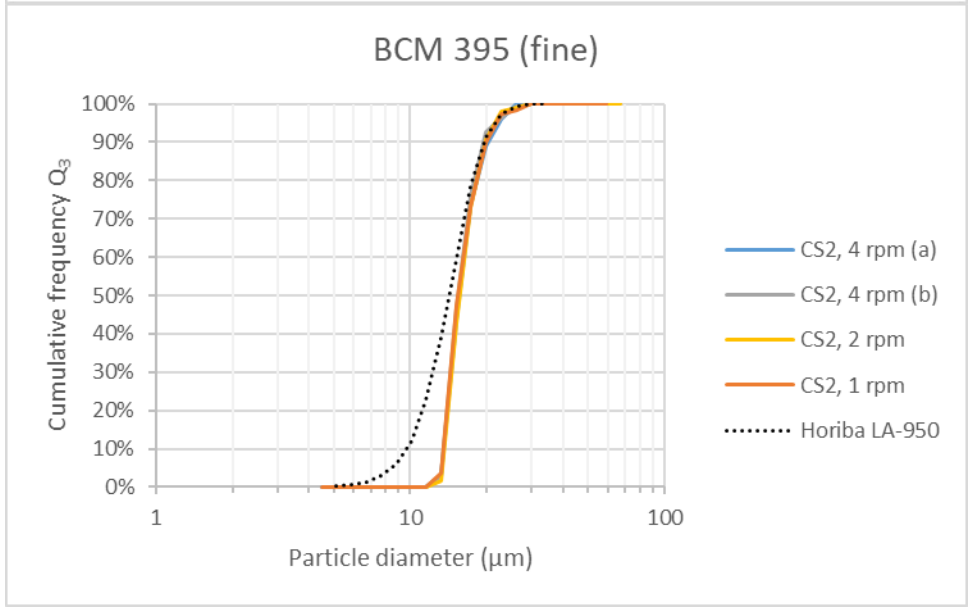
Horiba LA-950

- Median of particle size is slightly smaller than obtained from HiWatch CS2.

For all size distributions, the same binning was used.

All frequencies are volumetric.





Comparison HiWatch CS2 - Horiba

Median Particle Diameters, 6 – 25 g/min. Fine Powder

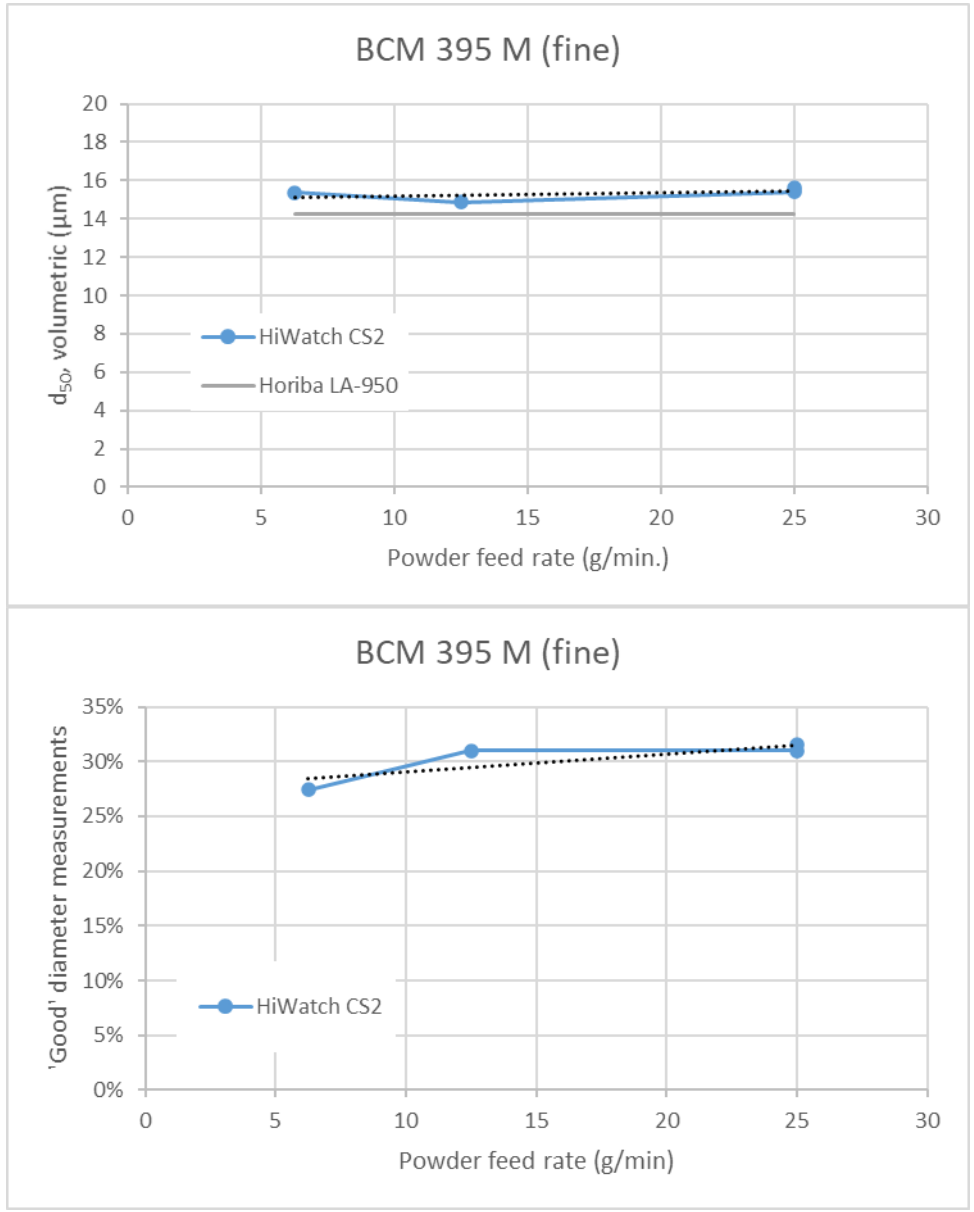
HiWatch CS2

- Sizing is not biased by powder feed rate.
- Fraction of ‘good’ diameter measurements 31% – 32%, except at 6 g/min. (27%).
- Algorithm to select ‘good’ measurements obviously works effectively.

Horiba LA-950

- Median of particle size is slightly smaller than obtained from HiWatch due to detection limit of the CS2.

All median particle diameters are volumetric.



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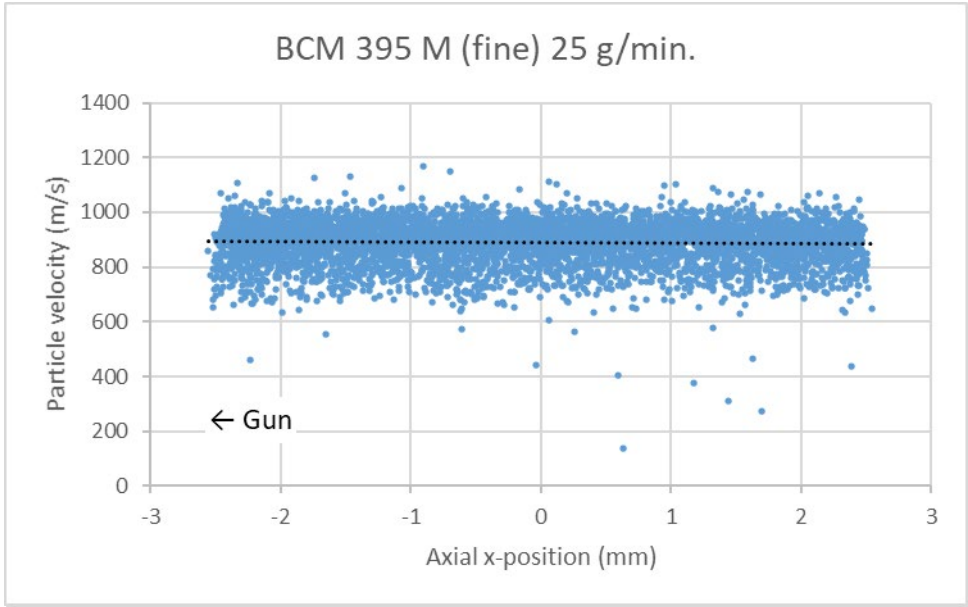
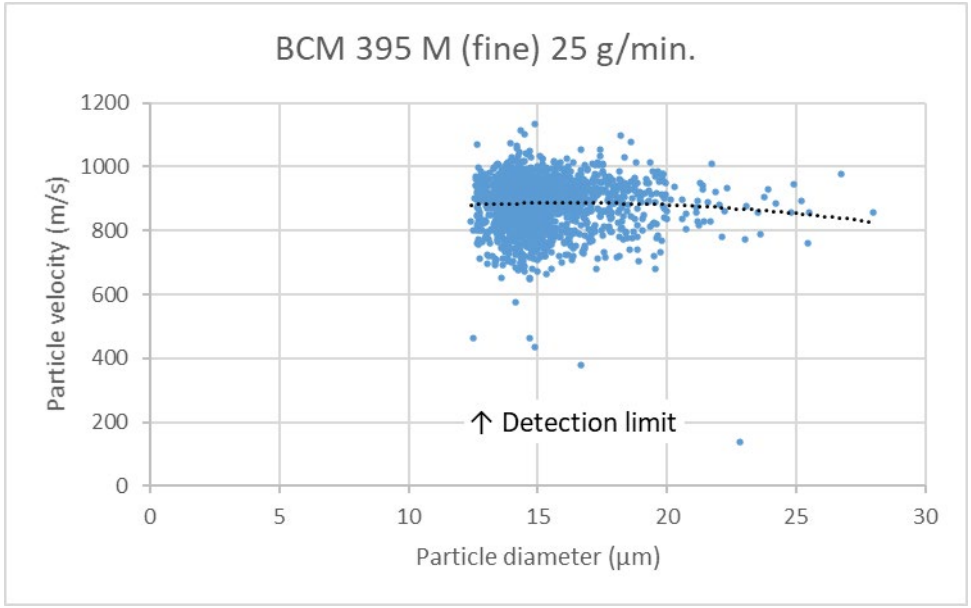
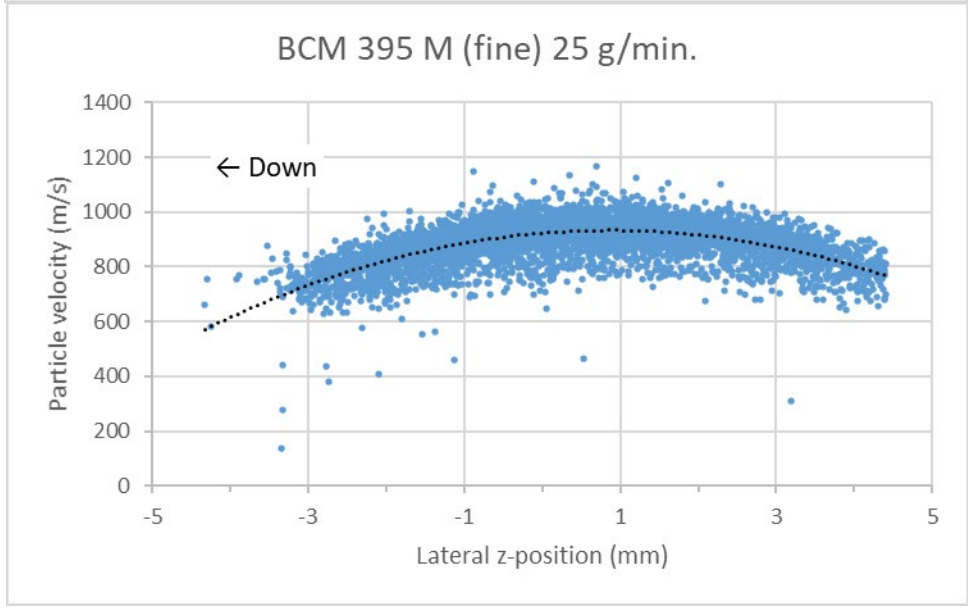
Results: HiWatch CS2

Particle Axial Velocities, 25 g/min. Fine Powder

- No significant velocity drop in axial direction
- Highest velocities in jet center at z = 1 mm
- Larger Particles slightly slower than smaller ones
- Lower detection limit Ø ≈ 12.5 mm







Results: HiWatch CS2

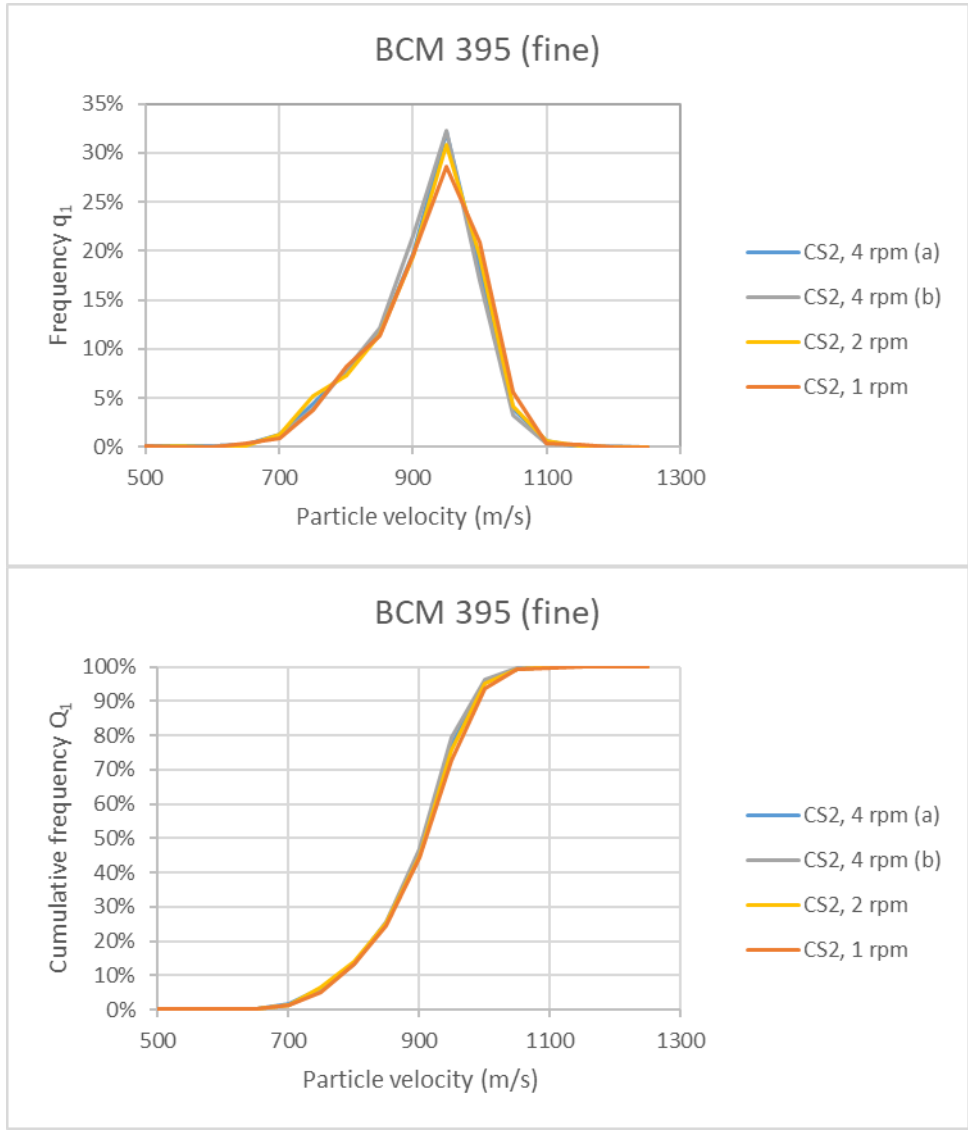
Particle Velocity Distributions, 6 – 25 g/min. Fine Powder

HiWatch CS2

- Slightly increasing particle velocities at smaller powder feed rates
- Good repeatability

For all size distributions, the same binning was used.

All frequencies are by particle counts.



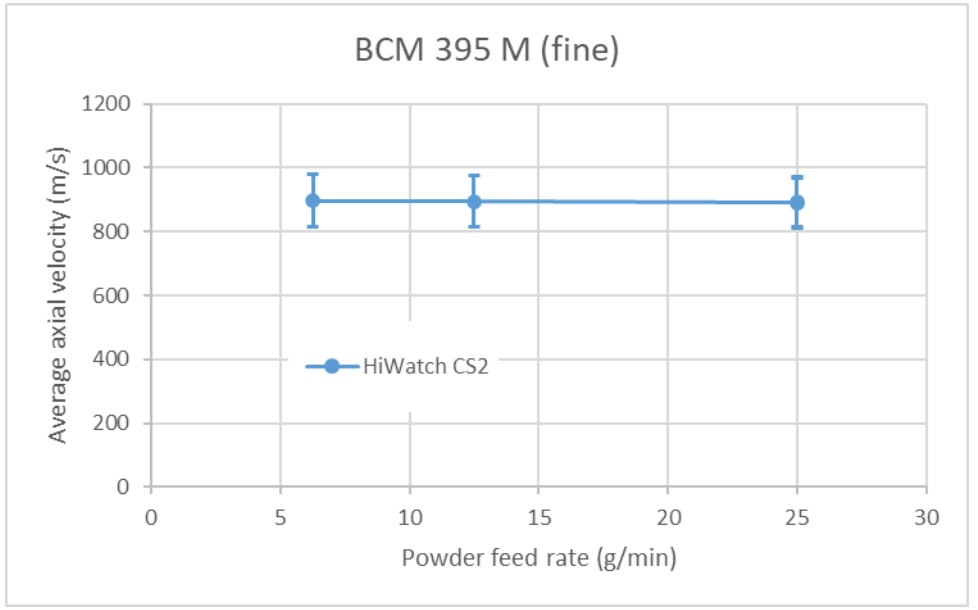
Results: HiWatch CS2

Average Particle Velocities, 6 – 25 g/min. Fine Powder

HiWatch CS2

- Average velocities and standard deviations not affected by powder feed rate.

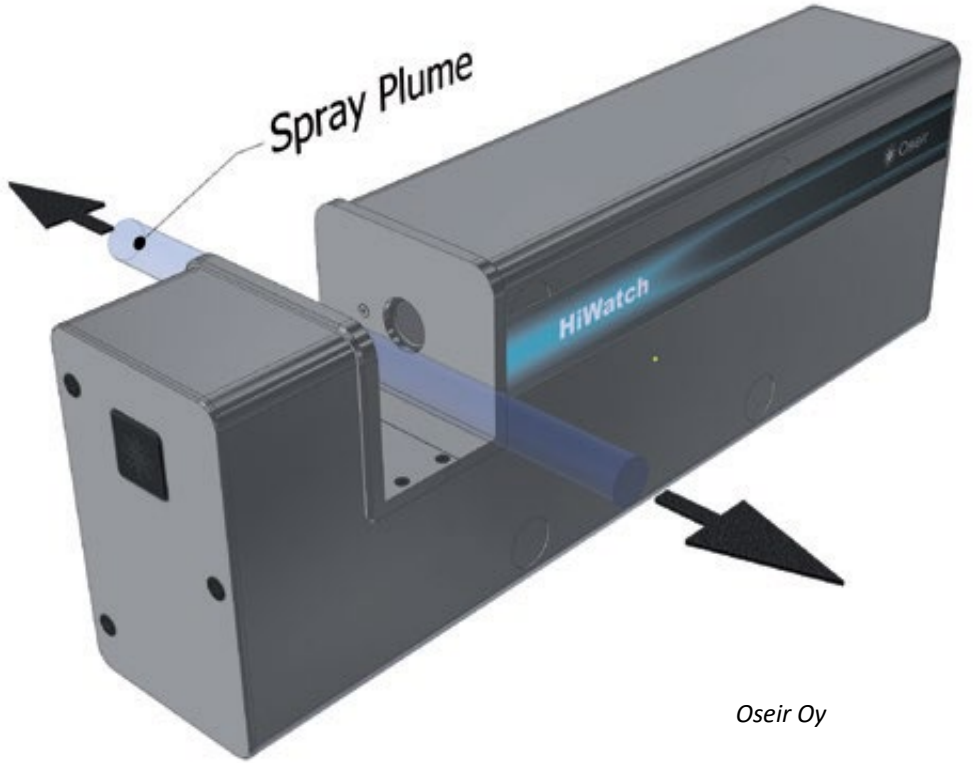
All average particle velocities are by particle counts.



Measuring Particle Position, Velocity, and Size

Particle tracking velocimetry (PTV) by Oseir HiWatch HR2

Measurement principle	**Laser illumination and shadow imaging**
Measurement area	≈ 8 mm lateral x 6 mm axial
Measurement depth	≈ 400 µm
Particle velocity range	0 – 2000 m/s
Particle diameter range	5 – 1000 µm
Capture speed	> 10 fps
Camera resolution	4000 x 3000
Laser wavelength	≈ 800 nm



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Measuring Particle Velocity, Size, and Flux

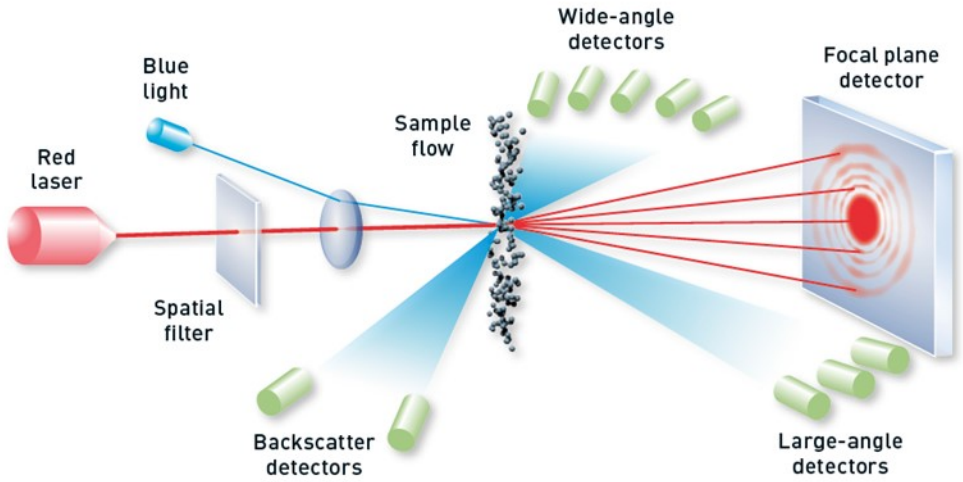
Tecnar Cold Spray Meter (CSM)

Measurement principle	**backscattered laser light, double-slit mask**
Measurement area	Ø 0.4 mm x 1.9 mm
Particle velocity range	50 – 1200 m/s
Particle diameter range	10 – 300 µm
Working distance	100 mm from spray gun axis
Laser power	3.3 W
Laser wavelength	≈ 790 nm
Laser beam divergence	70 mrad

Tecnar Ltd

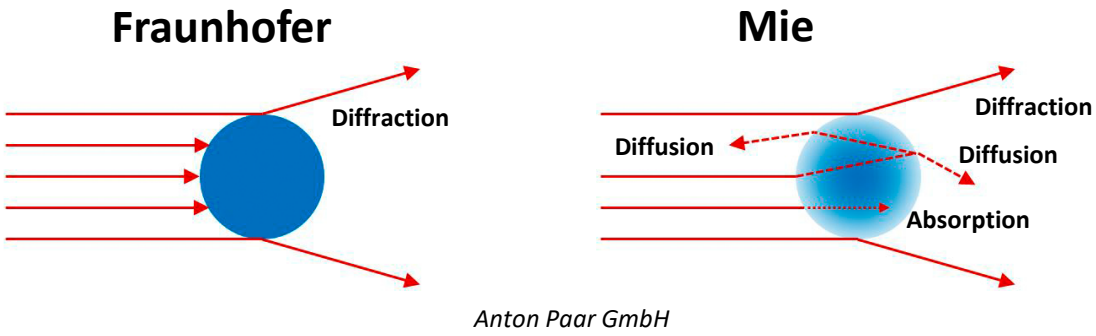
Measuring Particle Size

Horiba LA-950

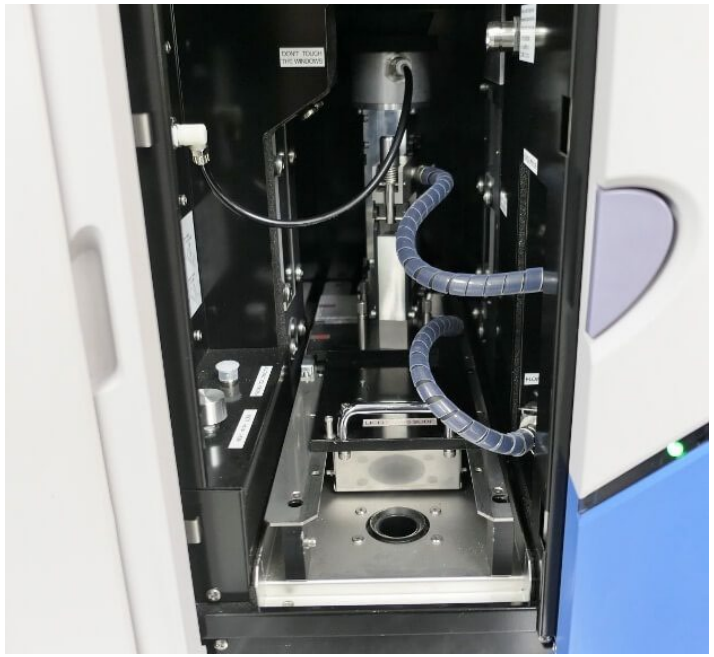


Malvern Panalytical Ltd

Measurement principle	**Laser diffraction**
Measurement range	0.01 – 3.000 µm
Accuracy	± 0.6% of NIST standard
Precision	± 0.1% coeff. of var. of NIST standard
Capture speed	5000 scans/s
Evaluation approach	Fraunhofer, Mie scattering
Laser wavelength	650 nm Laser diode 5.0 mW 405 nm light emitting diode 3.0 mW



Anton Paar GmbH



Horiba GmbH

Investigated Cases with HiWatch HR2, CSM, and Horiba

Cold Spray System Impact 5/11, N_2 , 80 m³/h (3.7 – 4.6 MPa), 600 – 1100°C, Spray Distance 60 mm

IN 718 **fine** powder (BCM 411/395 M): Oerlikon Metco AE 10718, -22 / +5 µm

d_{10} = 9.5/9.6 µm

d_{50} = 14.1/14.2 µm

d_{90} = 19.4/19.6 µm

Feed rate 15.0 g/min

Titanium **coarse** powder (TiM 596 X): Eckart TLS Ti Gd1, -53 / +20 µm

d_{10} = 21.6 µm

d_{50} = 36.6 µm

d_{90} = 54.1 µm

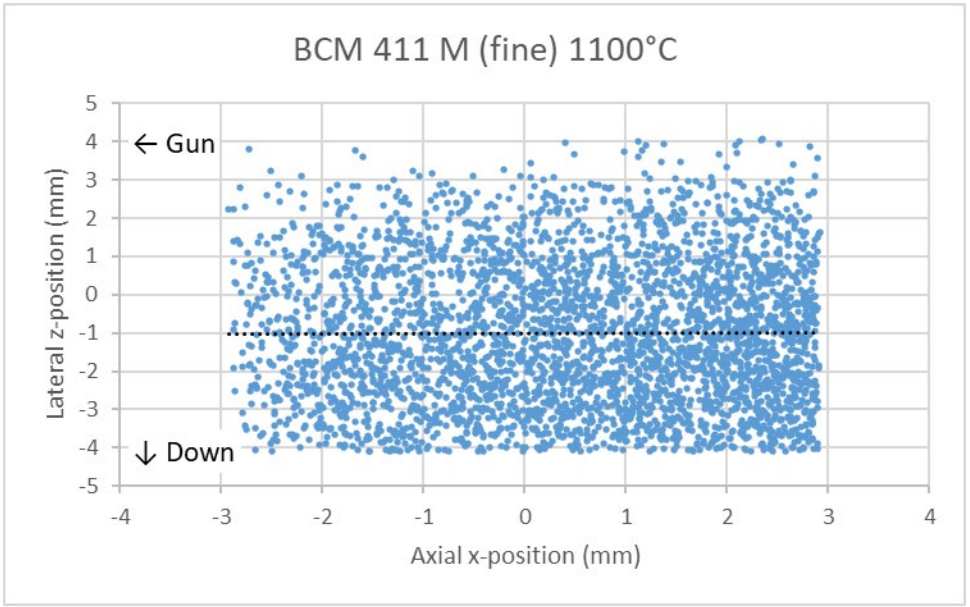
Feed rate 14.6 g/min

Particle size distribution by laser diffraction

Results: HiWatch HR2

Local Particle Distribution of Fine Powder, 1100°C

- 3495 particles
- Center of measured particle distribution 1 mm below torch axis
- Jet center obviously even deeper as particles with a lateral position < −4 mm are not covered.
- Particle density slightly decreases as axial position is shifted towards the torch.



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Comparison: HiWatch HR2-Horiba

Particle Diameters of Fine Powder, 600 – 1100°C

HiWatch HR2

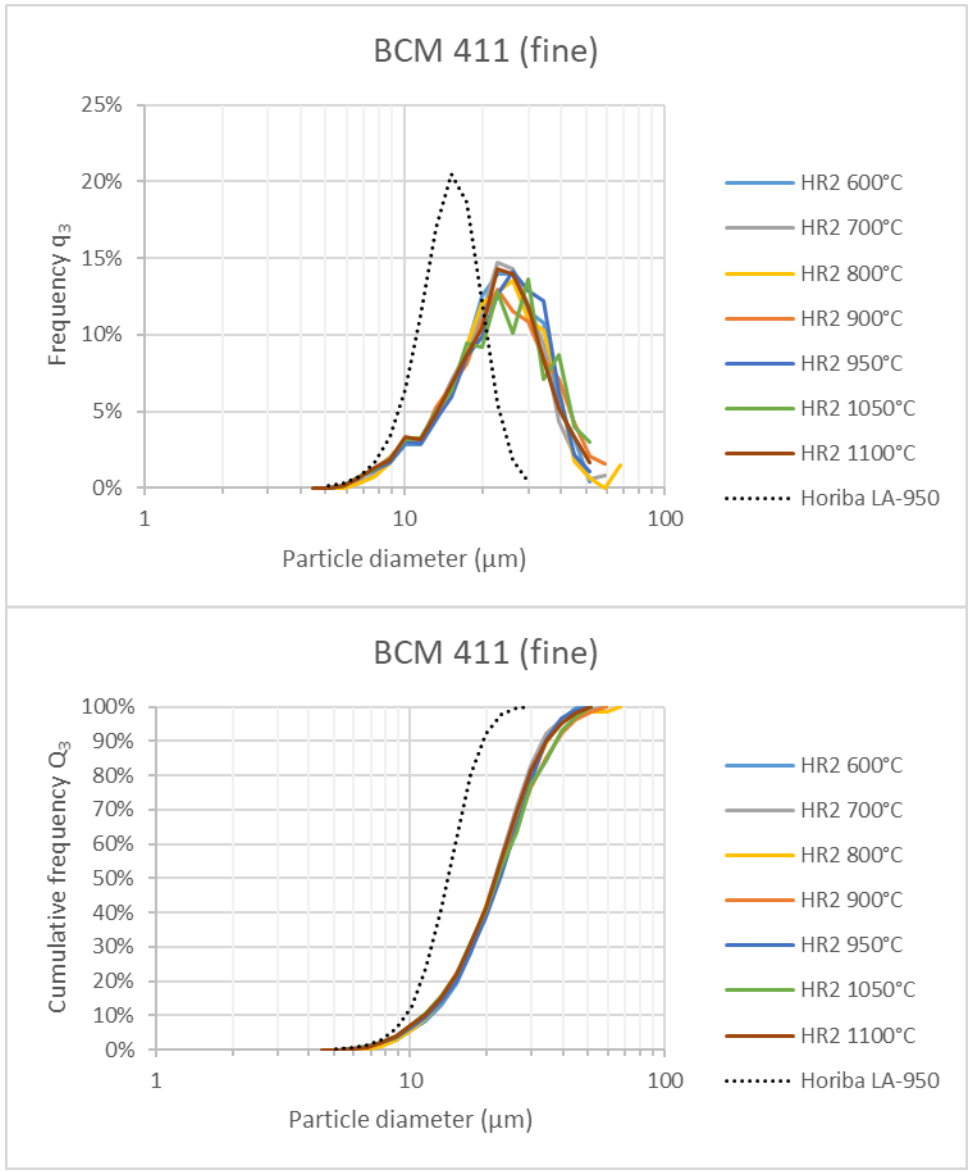
- Sizing is not biased by working gas temperature.
- Density distributions show differences in position and shape, obviously bias by larger particles.
- These differences are emphasized by the volumetric evaluation.

Horiba LA-950

- Median of particle size is smaller than obtained from HiWatch.
- Shape of density distribution is more narrow.

For all size distributions, the same binning was used.

All frequencies are volumetric.



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Comparison: CSM-Horiba

Particle Diameters of Fine Powder, 600 – 1100°C

CSM

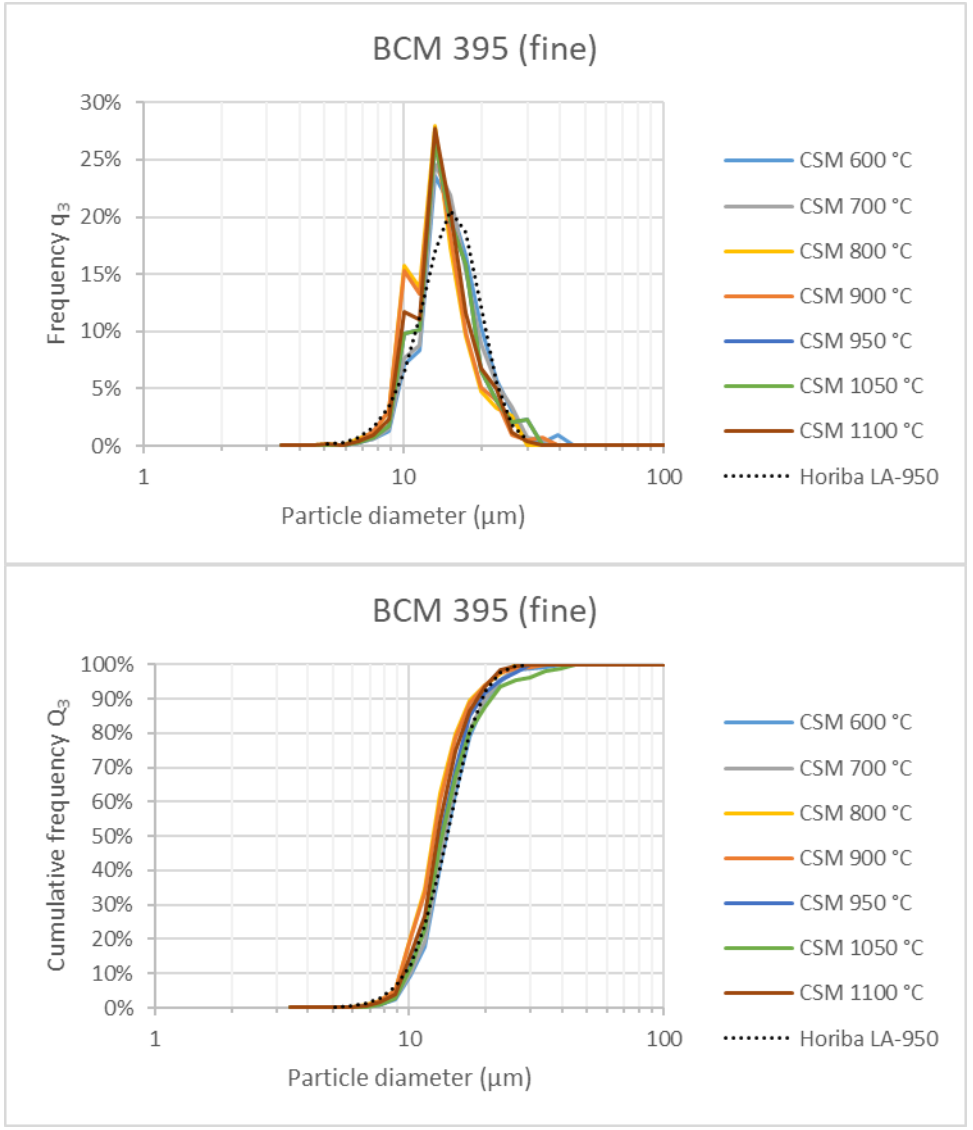
- Sizing is not biased by working gas temperature.
- Median of particle size is similar to Horiba due to calibration.

Horiba LA-950

- Shapes of the distributions agree reasonably with CSM.

For all size distributions, the same binning was used.

All frequencies are volumetric.



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Comparison HiWatch HR2-CSM-Horiba

Median Particle Diameters of Fine Powder, 600 – 1100°C

HiWatch HR2

- Sizing is not biased by working gas temperature.
- Fraction of ‘good’ diameter measurements slightly decreases with increasing working gas temperature (increasing turbulence?).
- Algorithm to select ‘good’ measurements obviously works effectively.

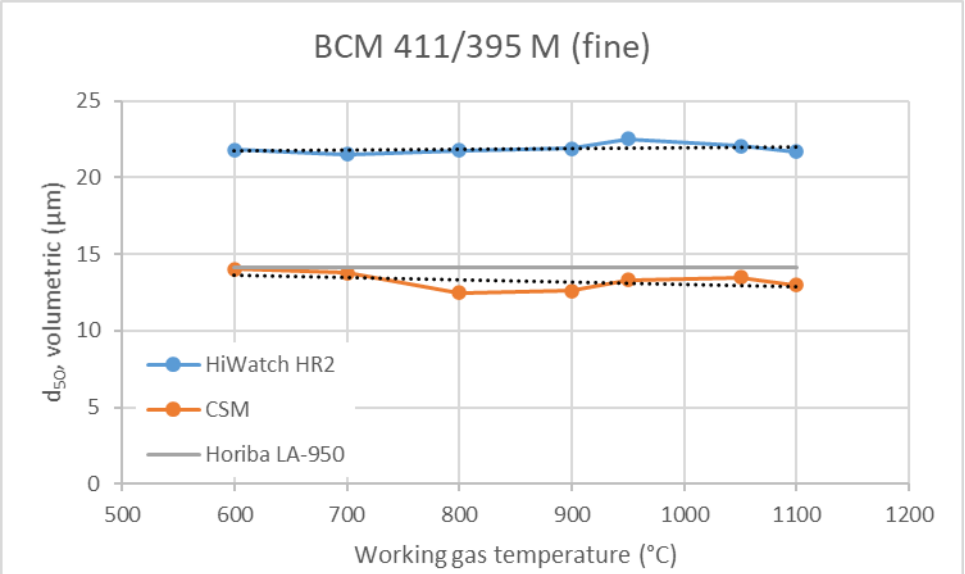
Horiba LA-950

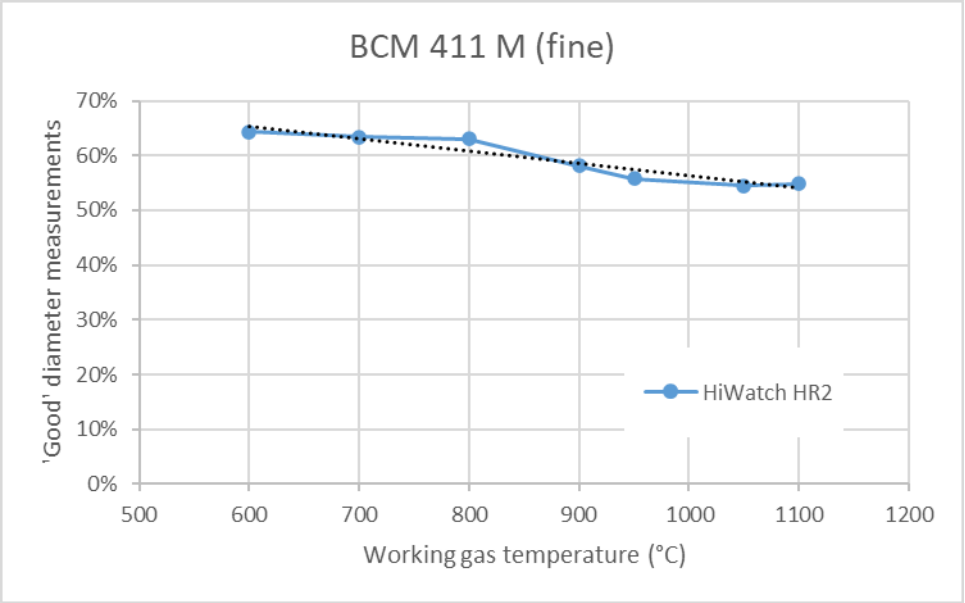
- Median of particle size is smaller than obtained from HiWatch.

CSM

Calibrated to match the d_{50} obtained by Horiba.

All median particle diameters are volumetric.





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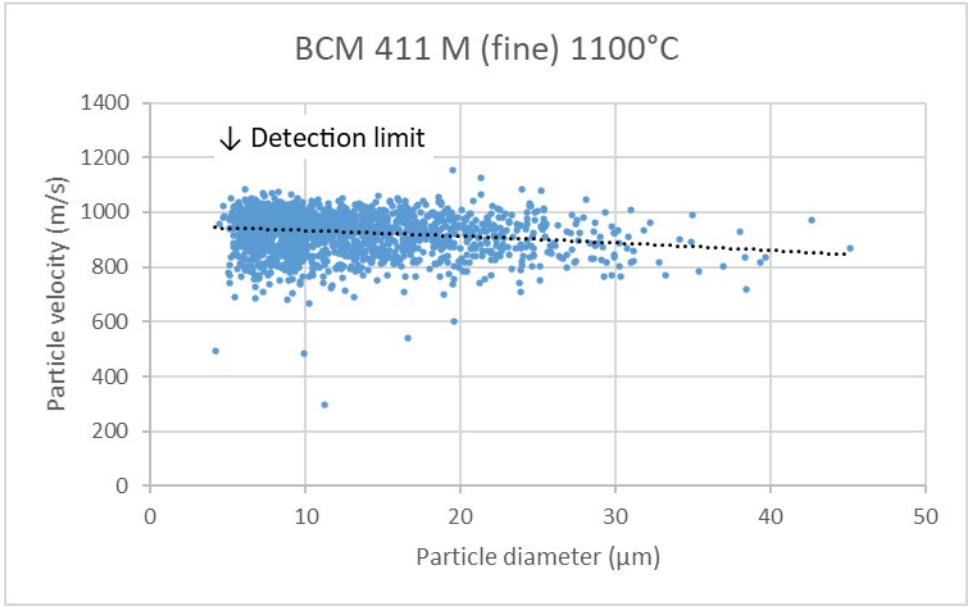
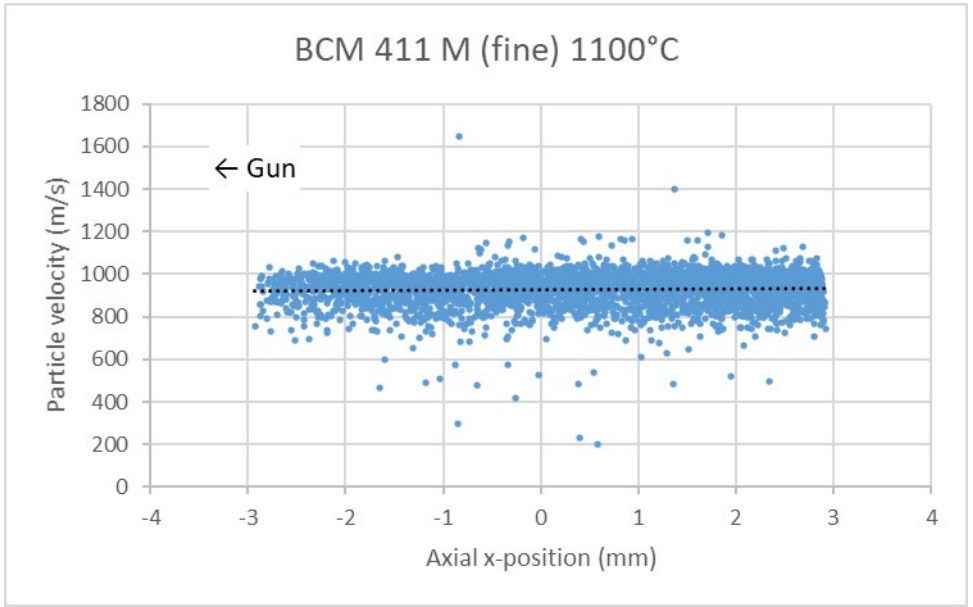
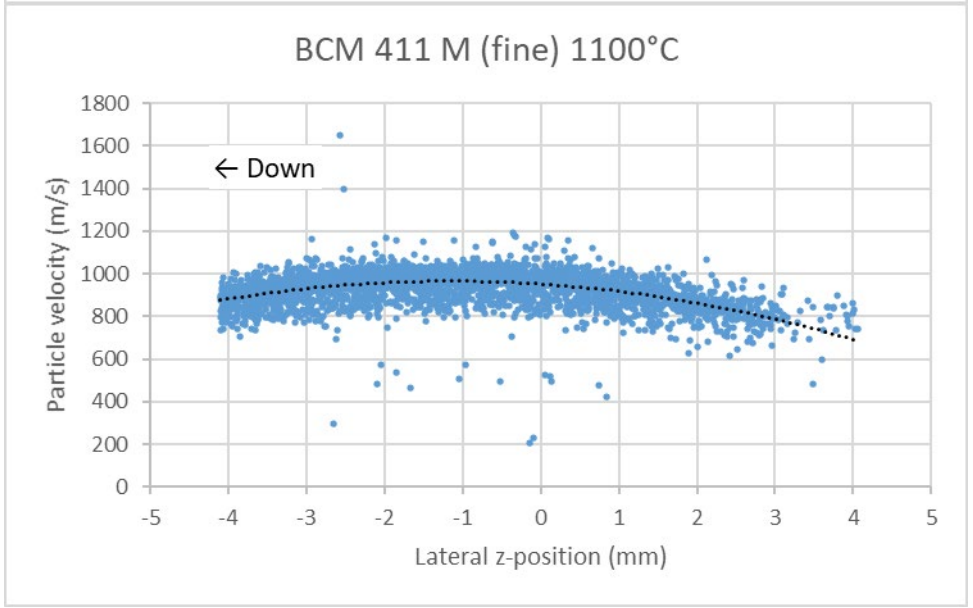
Results: HiWatch HR2

Particle Axial Velocities of Fine Powder, 1100°C

- No significant velocity drop in axial direction
- Highest velocities in jet center at z = −1 mm
- Larger Particles slightly slower than smaller ones
- Lower detection limit approx. Ø 5 µm (similar to CSM)







Results: HiWatch HR2

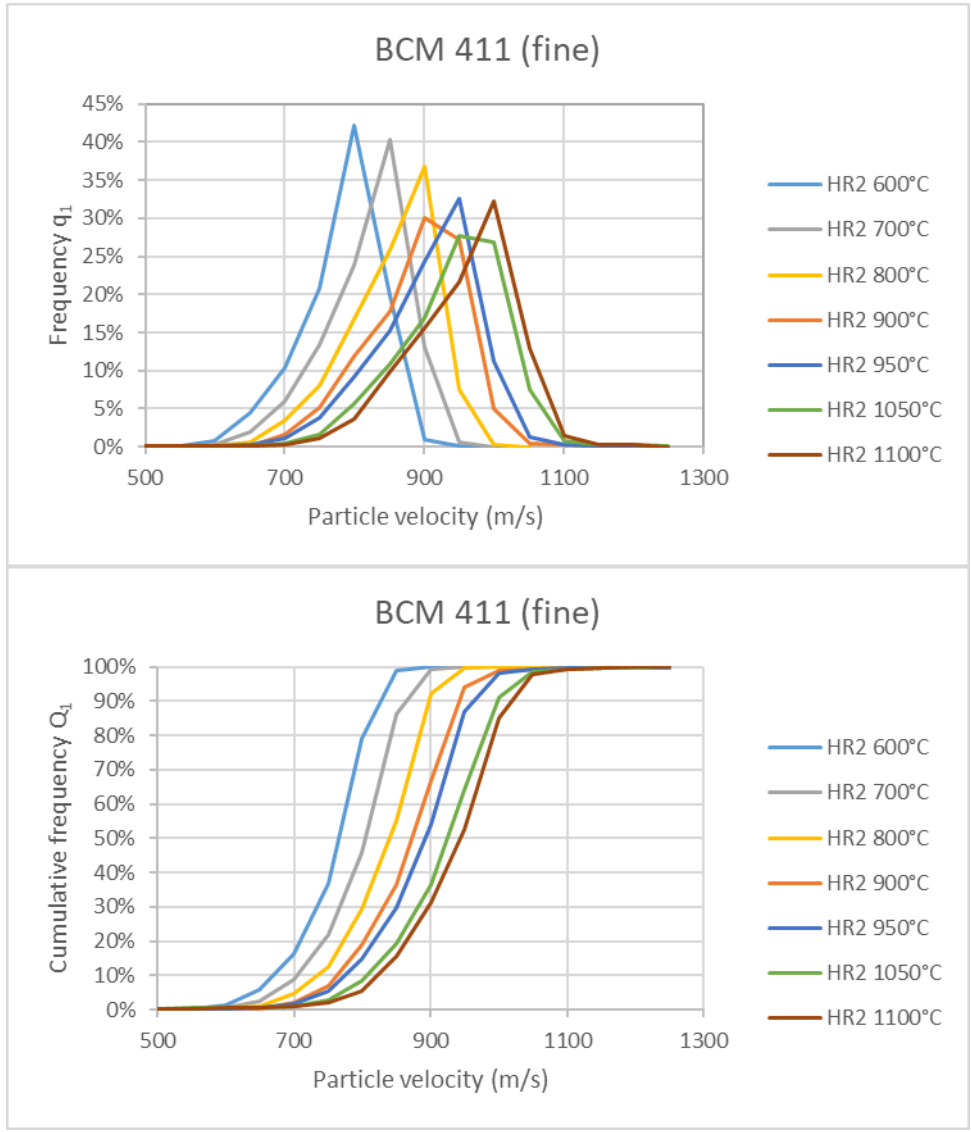
Particle Velocity Distributions of Fine Powder, 600 – 1100°C

HiWatch HR2

- Increasing particle velocities with increasing working gas temperature
- Widths of distributions slightly increase with increasing working gas temperature.

For all size distributions, the same binning was used.

All frequencies are by particle counts.



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Results: CSM

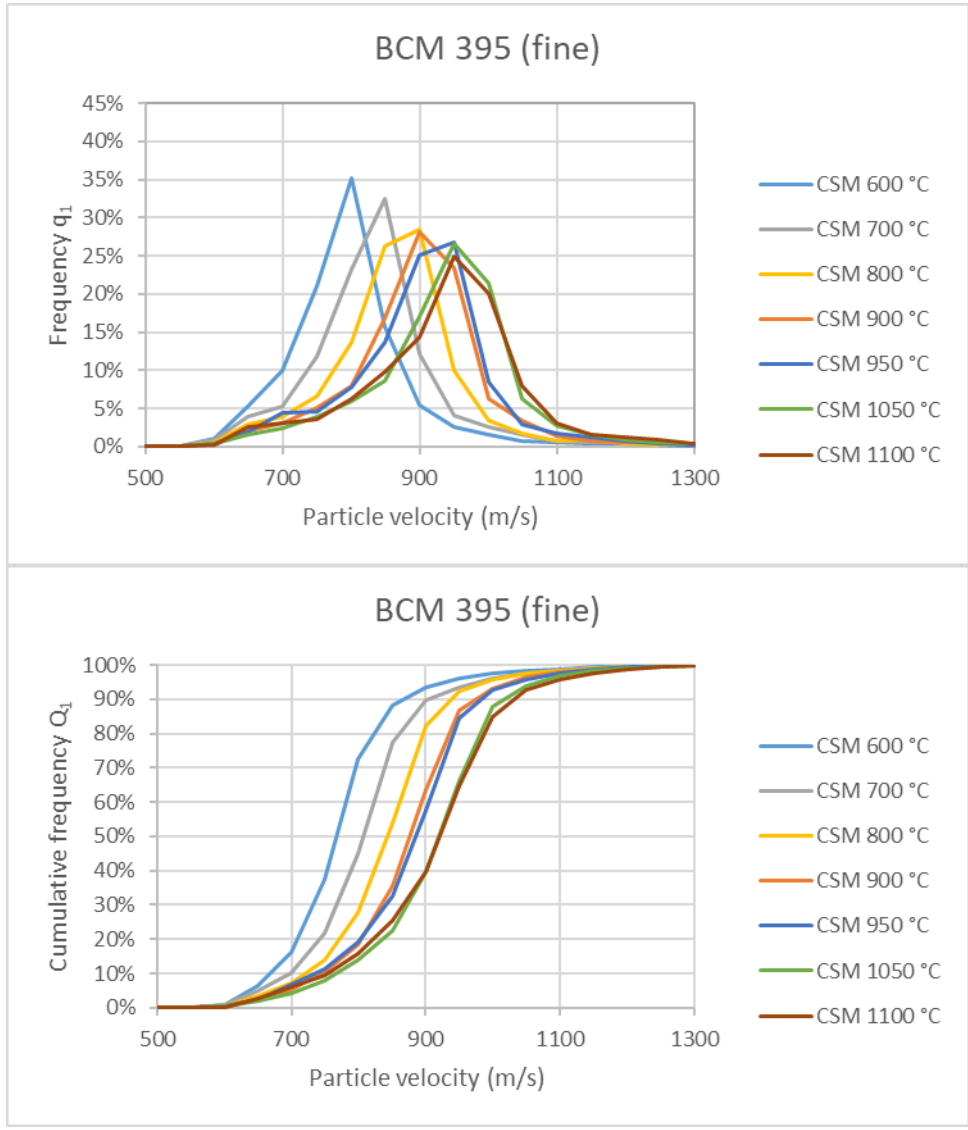
Particle Velocity Distributions of Fine Powder, 600 – 1100°C

CSM

- Same trends as for HiWatch.

For all size distributions, the same binning was used.

All frequencies are by particle counts.



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Comparison of Results

Average Particle Velocities of Fine Powder, 600 – 1100°C

HiWatch HR2

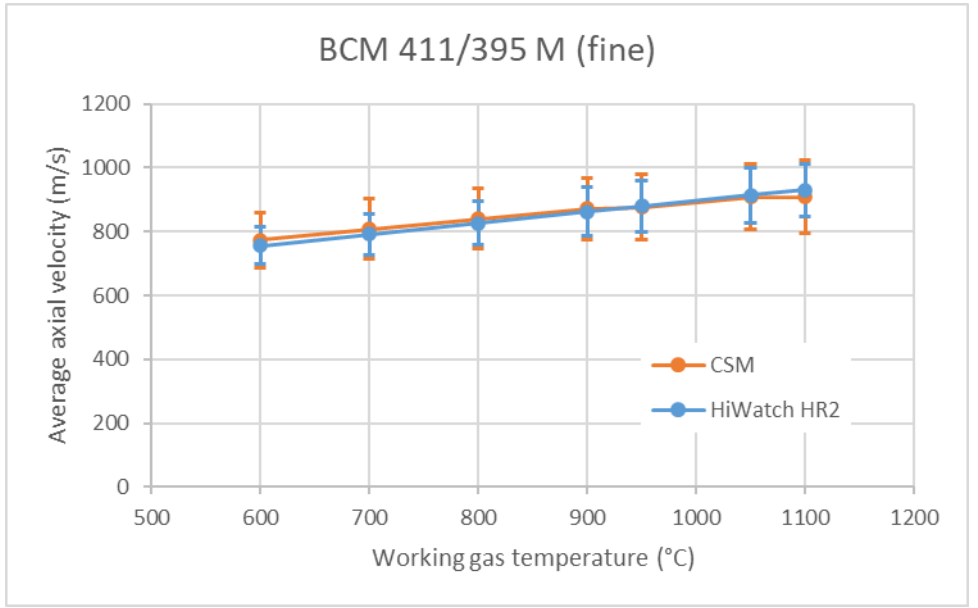
- Linear trend of particle velocities with increasing working gas temperature
- Standard deviations slightly increase with increasing working gas temperature.

CSM

- Same trends as with HiWatch.
- Overall standard deviation are slightly larger than with HiWatch.

Good agreement.

All average particle velocities are by particle counts.



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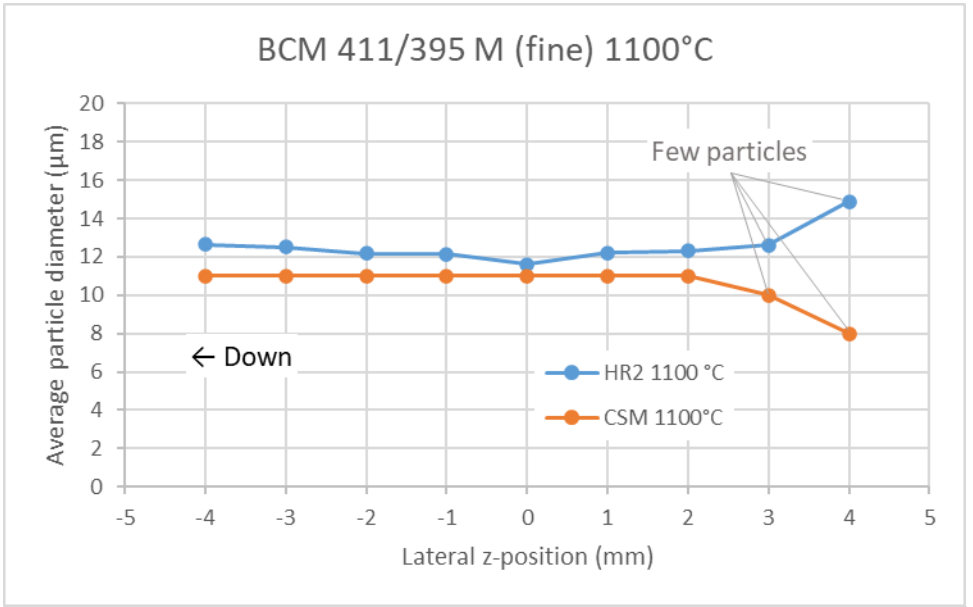
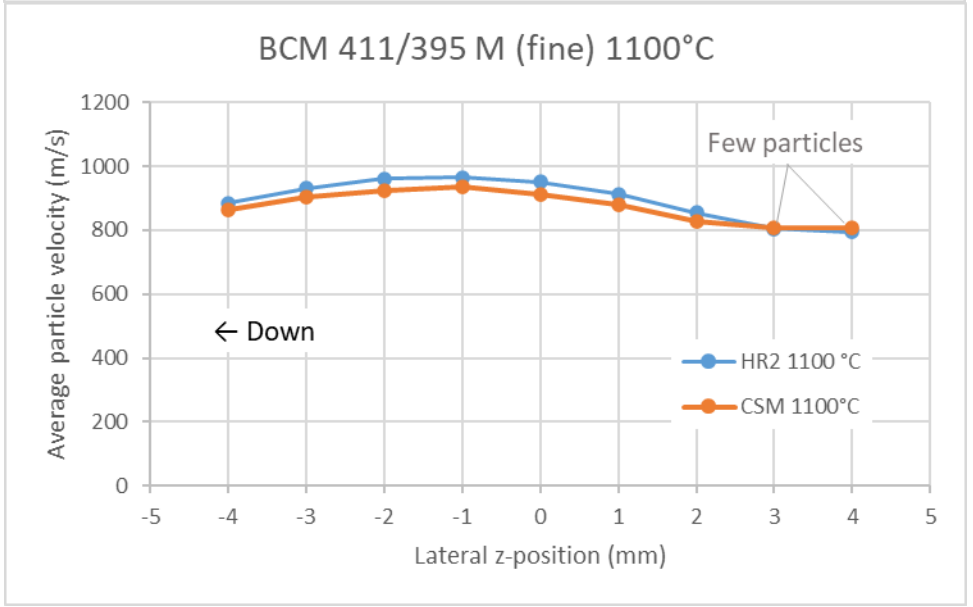
Comparison of Radial Scans

Average Particle Diameters and Velocities of Fine Powder, 1100°C

- **HiWatch HR2**: measurement area 48 mm²
  x = −3 mm … +3 mm, z = −4 mm … +4 mm
  particle data averaged in slices of Δz = 1 mm
- **CSM**: measurement area 0.13 mm²
  center at x = 0 mm, z = −4 mm … +4 mm
  particle data averaged for each integer z-coordinate
- **Good agreement** between HiWatch and CSM.
- At the upper plume edge (z = +3 mm and +4 mm) only few particles.
- Average particle diameters and velocities are by particle counts.





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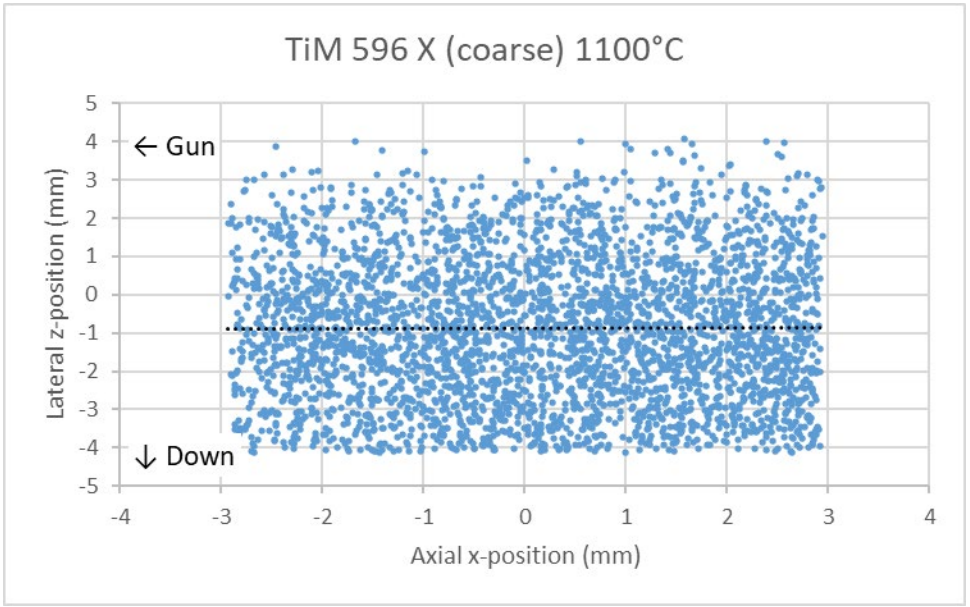
Results: HiWatch HR2

Local Particle Distribution of Coarse Powder, 1100°C

- 2823 particles
- Center of measured particle distribution 1 mm below torch axis
- Jet center obviously even deeper as particles with a lateral position < −4 mm are not covered.
- Particle density minimally decreases as axial position is shifted towards the torch.



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Comparison: HiWatch-Horiba

Particle Diameters of Coarse Powder, 600 – 1100°C

HiWatch HR2

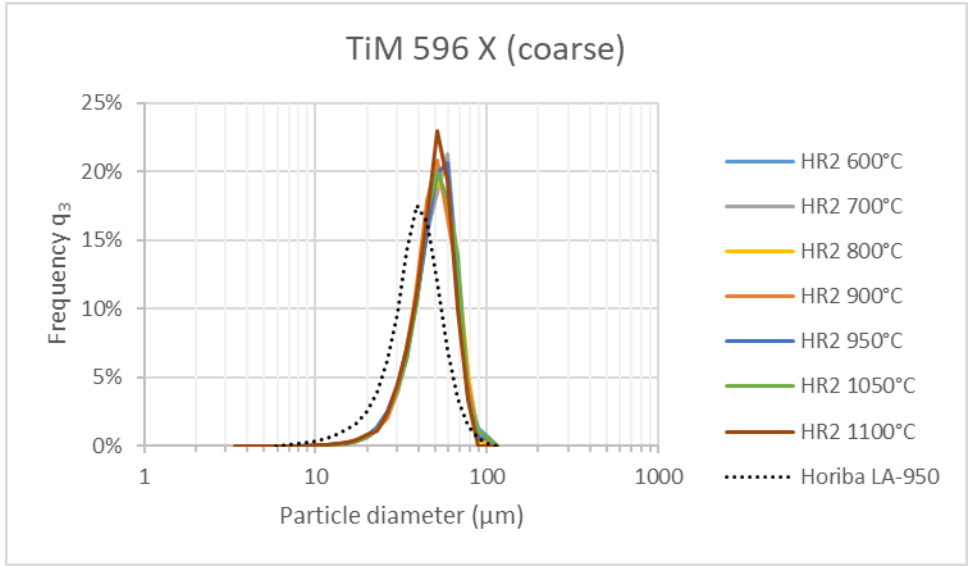
- Sizing is not biased by working gas temperature.
- Density distributions show differences in position and shape, obviously bias by larger particles.
- These differences are emphasized by the volumetric evaluation.

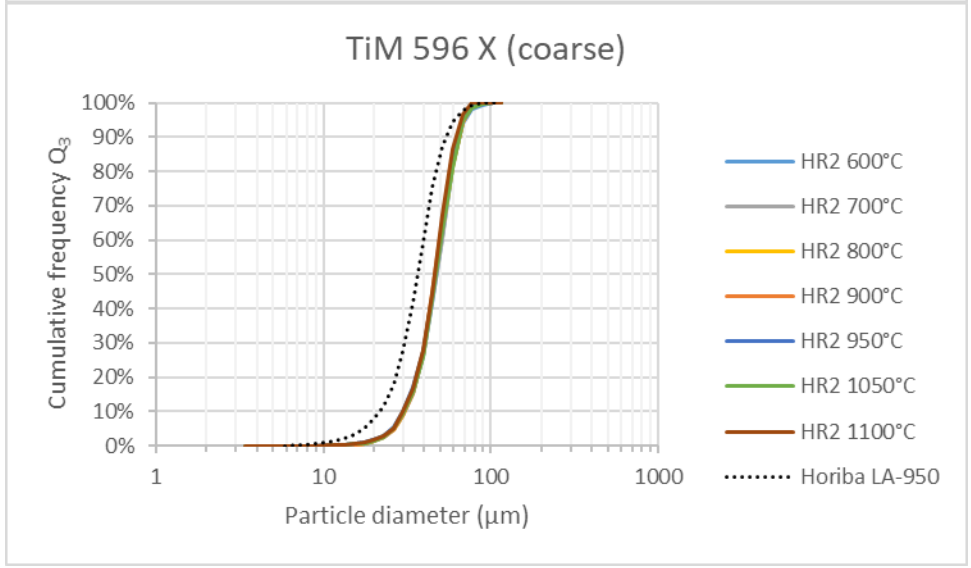
Horiba LA-950

- Median of particle size is smaller than obtained from HiWatch.
- Shape of density distribution is slightly wider.

For all size distributions, the same binning was used.

All frequencies are volumetric.





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Comparison: CSM-Horiba

Particle Diameters of Coarse Powder, 600 – 1100°C

CSM

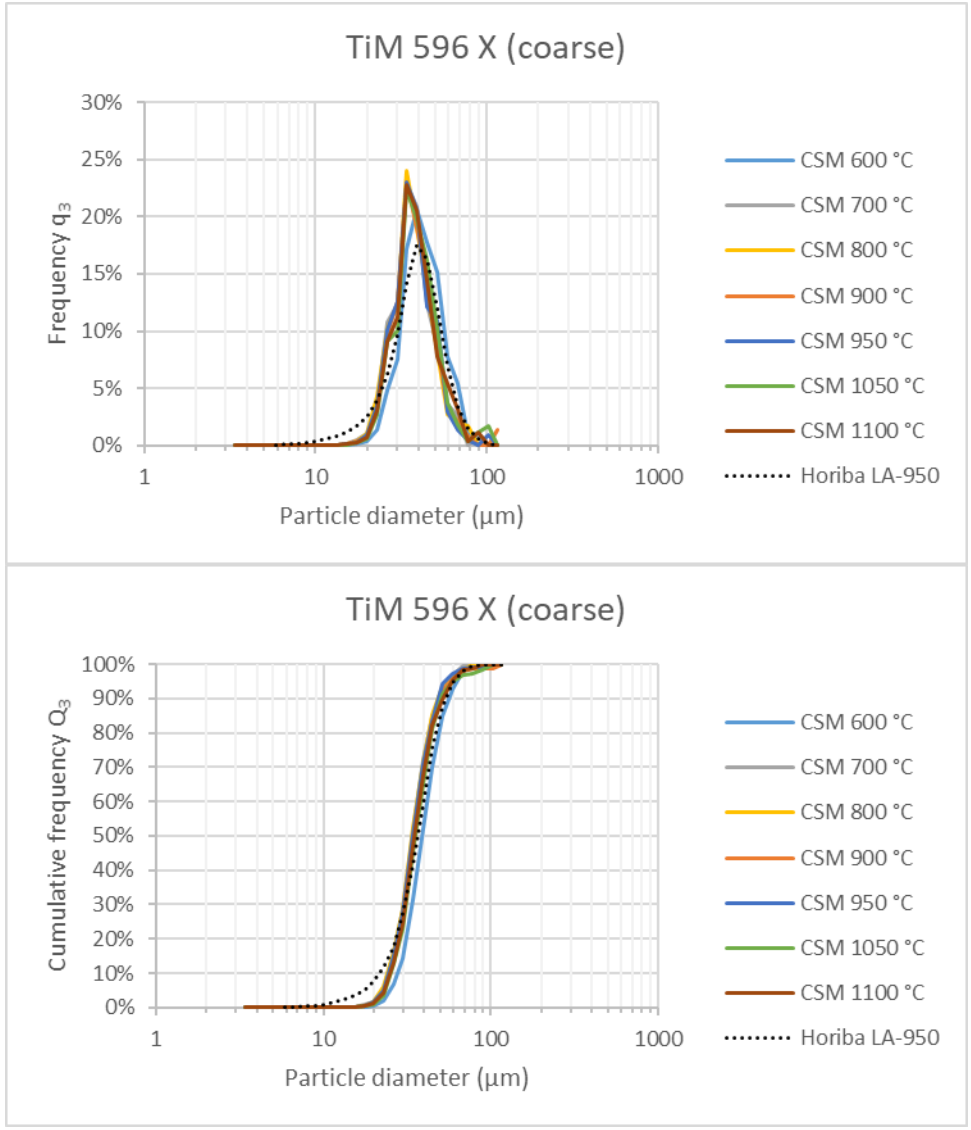
- Sizing is not biased by working gas temperature.
- Median of particle size is similar to Horiba due to calibration.

Horiba LA-950

- Shapes of the distributions agree reasonably with CSM.

For all size distributions, the same binning was used.

All frequencies are volumetric.



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Comparison: HiWatch HR2-CSM-Horiba

Median Particle Diameters of Coarse Powder, 600 – 1100°C

HiWatch HR2

- Sizing is not biased by working gas temperature.
- Fraction of ‘good’ diameter measurements decreases with increasing working gas temperature.
- Algorithm to select ‘good’ measurements obviously works effectively.

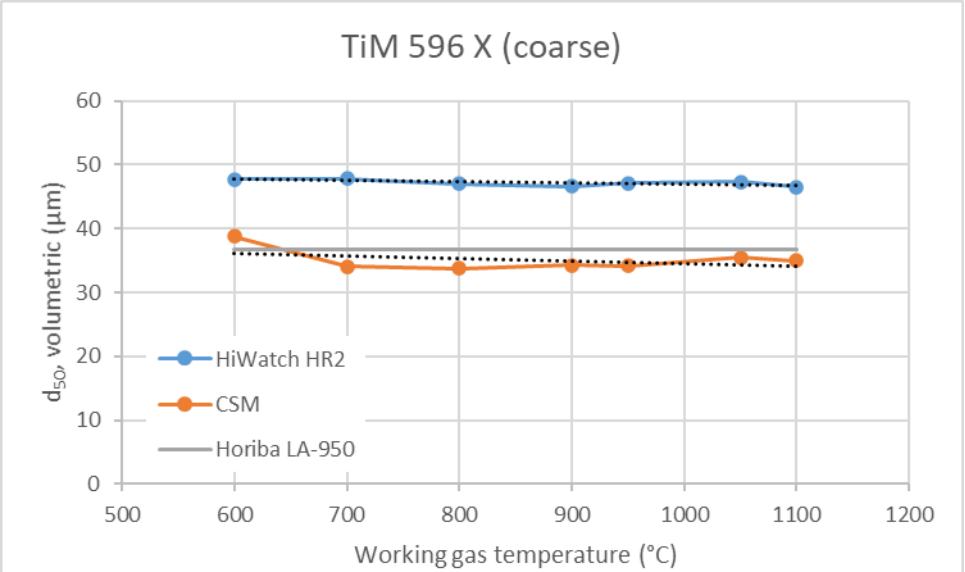
Horiba LA-950

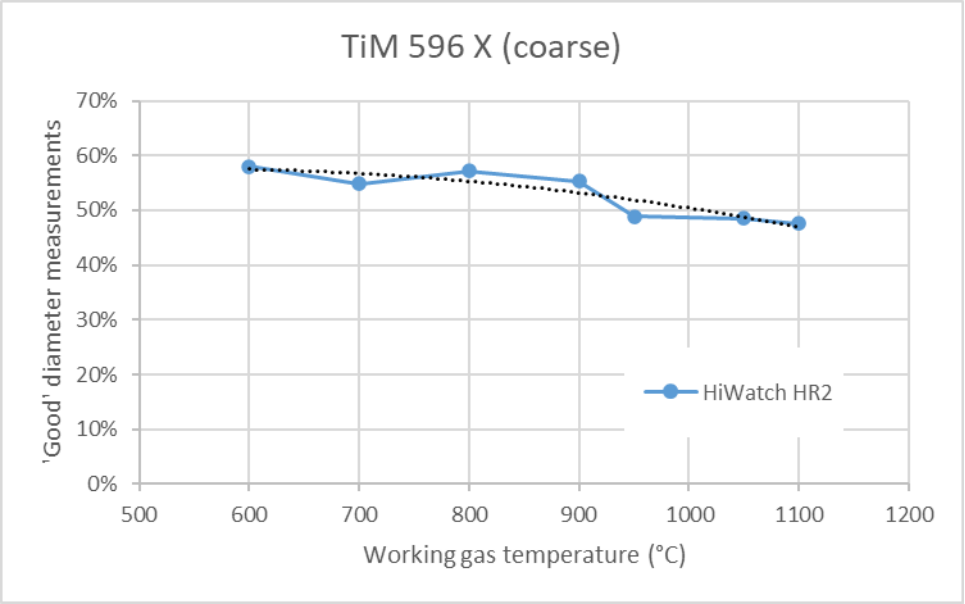
- Sizing is slightly biased by working gas temperature.
- Median of particle size is smaller than obtained from HiWatch.

CSM

Calibrated to match the d_{50} obtained by Horiba.

All median particle diameters are volumetric.



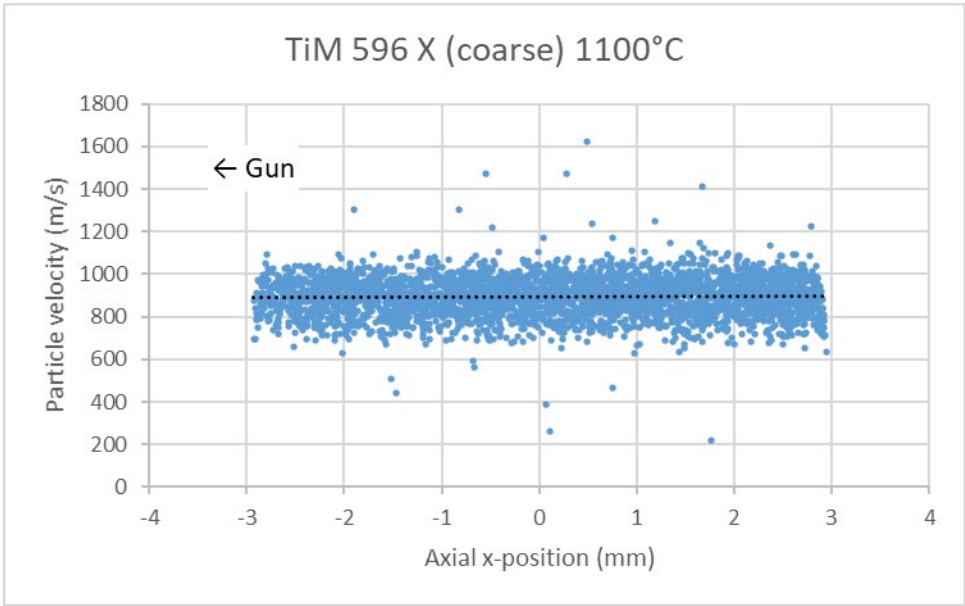


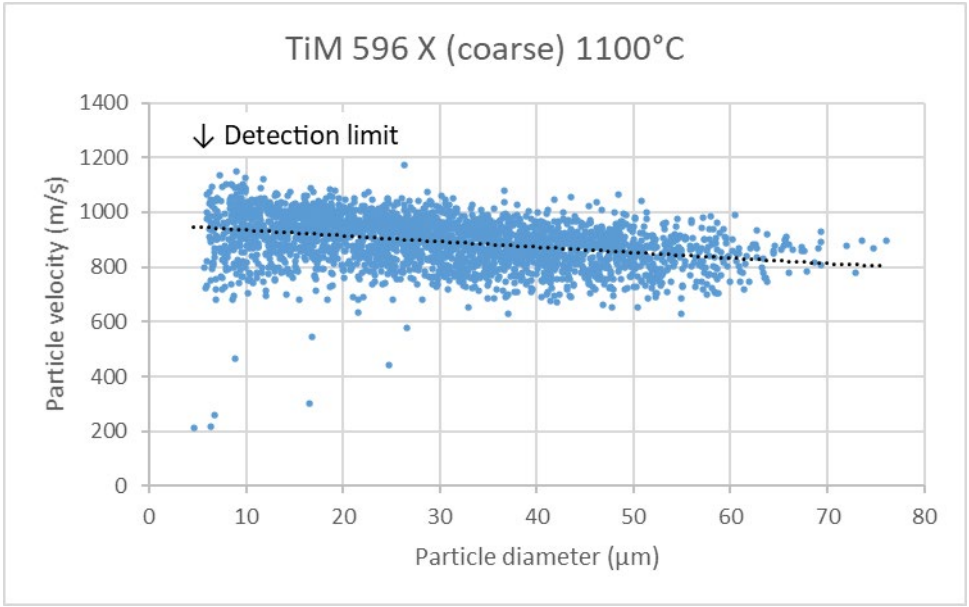
JÜLICH Forschungszentrum

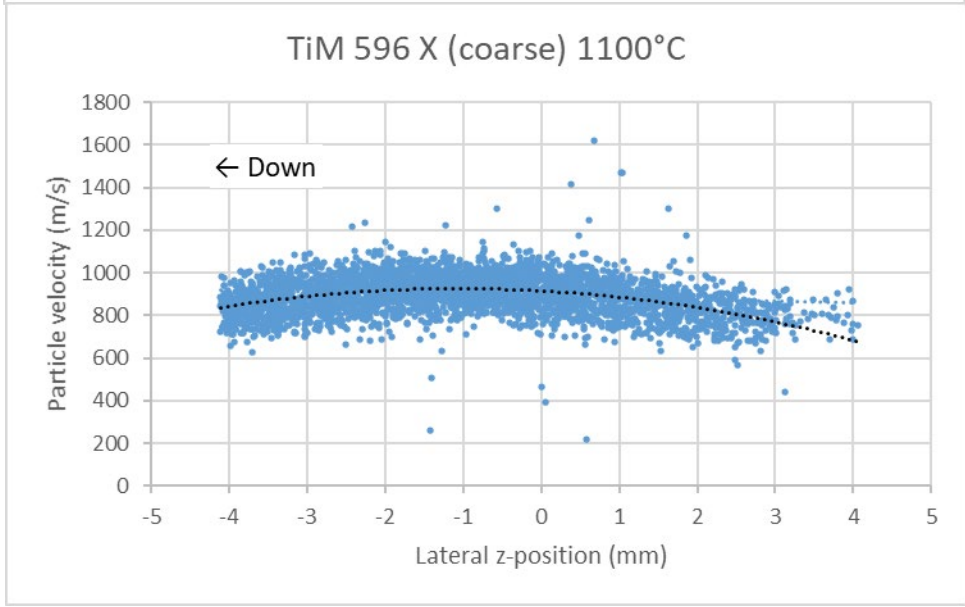
Results: HiWatch HR2

Particle Axial Velocities of Coarse Powder, 1100°C

- No significant velocity drop in axial direction
- Highest velocities in jet center at z = −1 mm
- Larger Particles slower than smaller ones
- Lower detection limit approx. Ø 5 µm







Results: HiWatch HR2

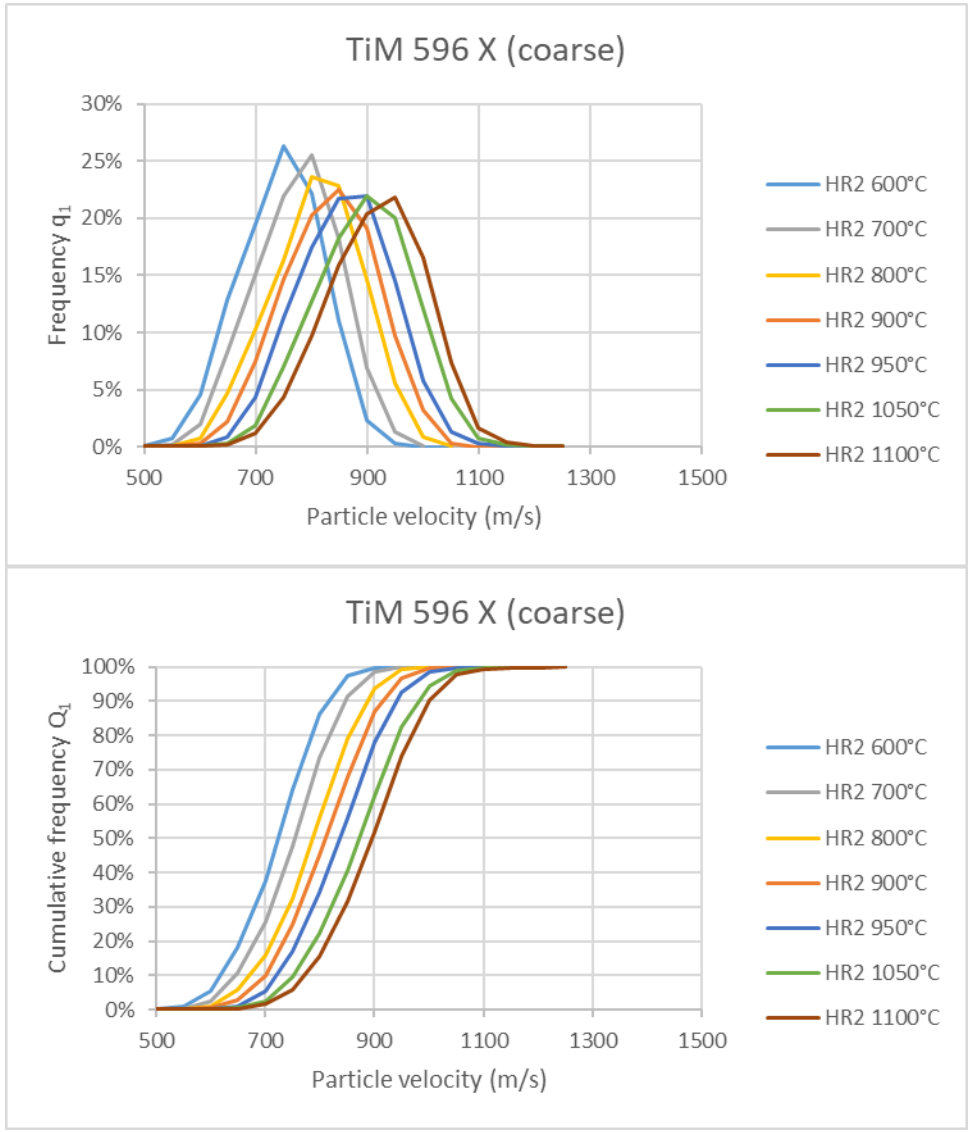
Particle Velocities of Coarse Powder, 600 – 1100°C

HiWatch HR2

- Increasing particle velocities with increasing working gas temperature
- Widths of distributions slightly increase with increasing working gas temperatures.

For all size distributions, the same binning was used.

All frequencies are by particle counts.



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Results: CSM

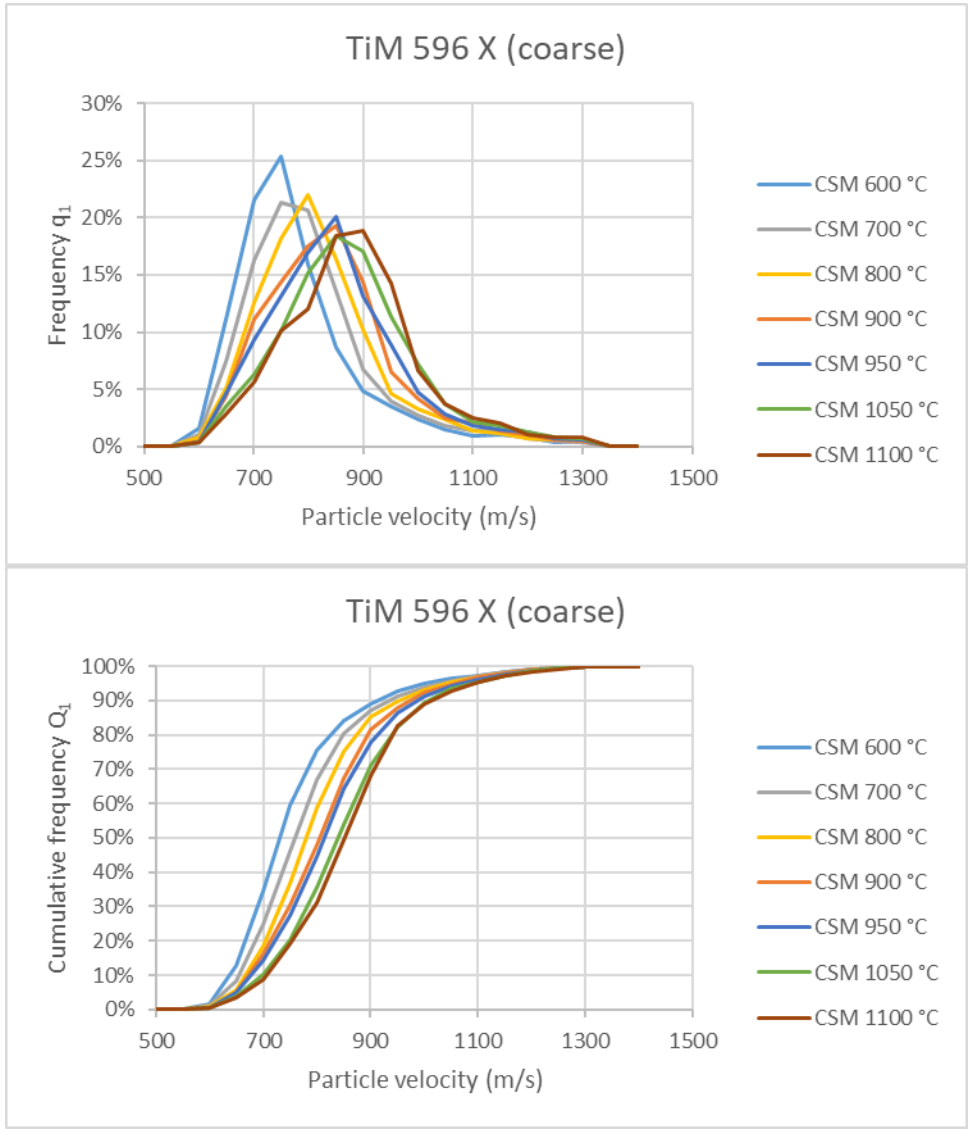
Particle Velocities of Coarse Powder, 600 – 1100°C

CSM

- Same trends as for HiWatch.

For all size distributions, the same binning was used.

All frequencies are by particle counts.



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Comparison of Results

Average Particle Velocities of Coarse Powder, 600 – 1100°C

HiWatch HR2

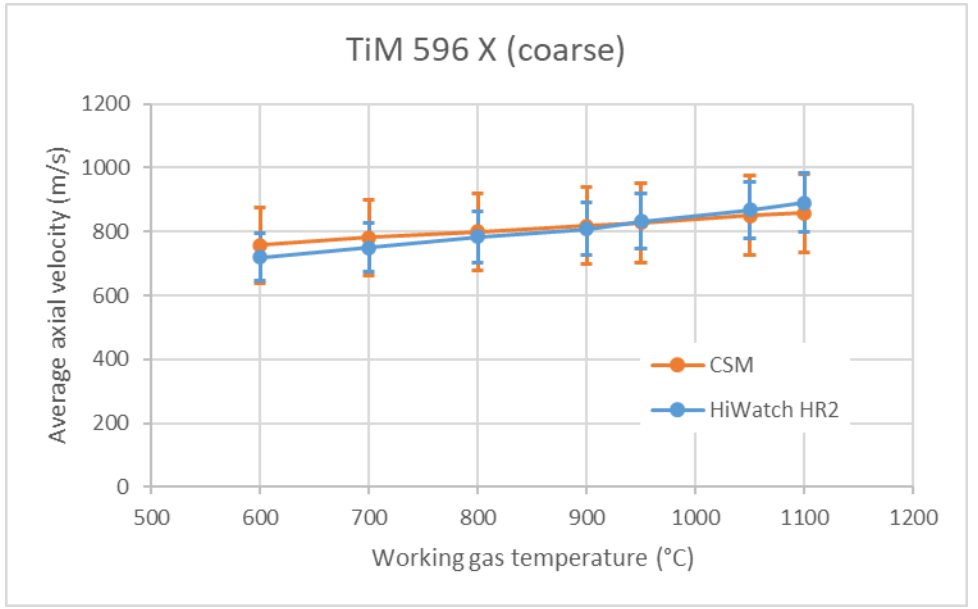
- Linear trend of particle velocities with increasing working gas temperature
- Standard deviations slightly increase with increasing working gas temperatures.

CSM

- Same trends as with HiWatch.
- Overall standard deviation are slightly larger than with HiWatch.

Good agreement.

All average particle velocities are by particle counts.



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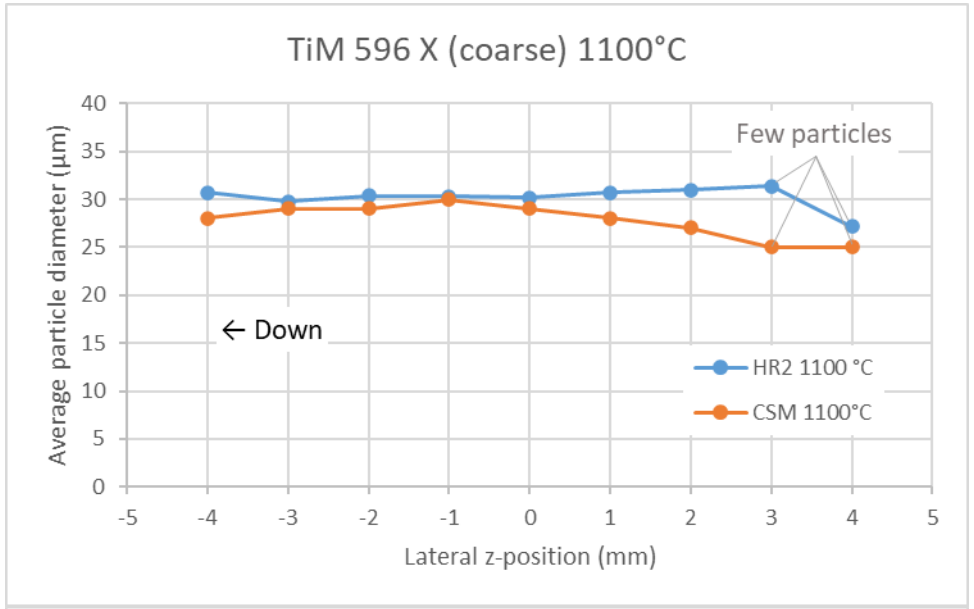
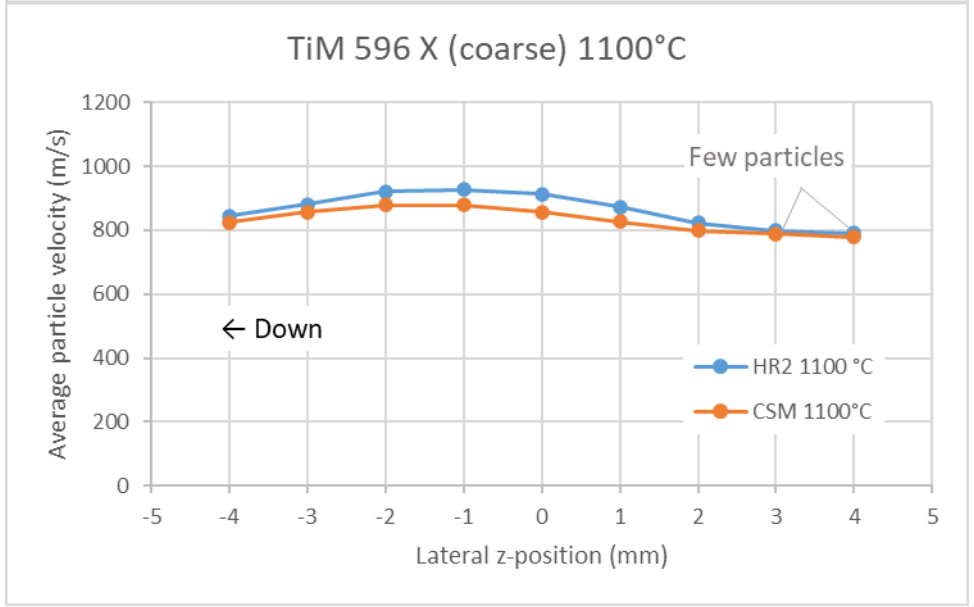
Comparison of Radial Scans

Average Particle Diameters and Velocities of Coarse Powder, 1100°C

- **HiWatch HR2**: measurement area 48 mm²
  x = −3 mm … +3 mm, z = −4 mm … +4 mm
  particle data averaged in slices of Δz = 1 mm
- **CSM**: measurement area 0.13 mm²
  center at x = 0 mm, z = −4 mm … +4 mm
  particle data averaged for each integer z-coordinate
- **Good agreement** between HiWatch and CSM.
- At the upper plume edge (z = +3 mm and +4 mm) only few particles.
- All average particle diameters and velocities are by particle counts.





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Conclusions

Testing of Diagnostic Systems for Measuring Particle Properties in Cold Spray

- The **HiWatch CS2** has a lower detection limit for particles less than 12 µm in diameter due to limited pixel resolution and sampling theorem issues. Thus, depending on the particle size distribution, the results may be biased by larger particles. On the other hand, the CS2 could underestimate particle size due to one-sided illumination.
- These two effects may balance each other out. Hence, the agreement with the laser diffraction data was fairly good. Nevertheless, the CS2 sizing should considered to be mostly qualitative.
- Velocity and position measurements by the CS2 were found to be plausible, repeatable, and not biased by process conditions (powder feed rate).

Conclusions

Testing of Diagnostic Systems for Measuring Particle Properties in Cold Spray

- The **HiWatch HR2** has a lower detection limit for particles less than 5 µm in diameters due to limited pixel resolution; this is considerably lower than for the CS2.
- The HR2 sizing shows a certain bias by larger particles. Thus, the results are in better agreement with the laser diffraction data for the coarser powder.
- Velocity and position measurements by the HR2 were found to be plausible, in very good agreement with the CSM results, and not biased by the powder size or process conditions (working gas temperature).

Thank you!