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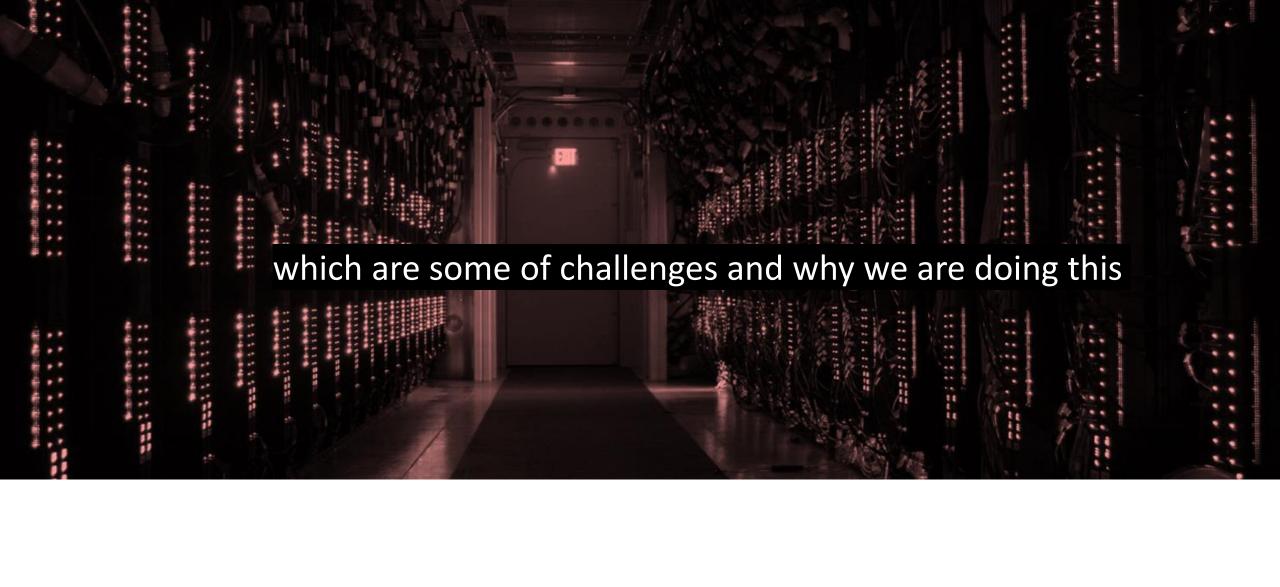
WHY are there challenges?



HOW to address them?



WHAT have we learned (thus far)

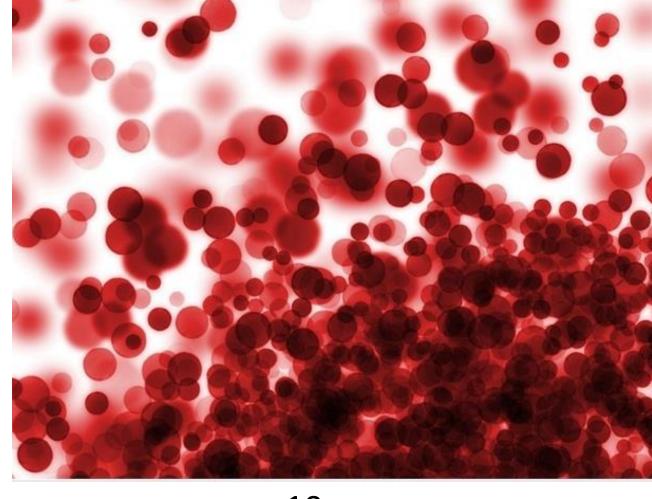


# type 1 challenges

particle size range



6 nm 'cell fuel' protein



10 μm human red cells

# type 2 challenges

engineering aspects

no industry-approved enclosure and sampling system specification...yet

legacy aerosol models fall short due to complex flow patterns and interactions bias and complexity of relying only on experimental methods



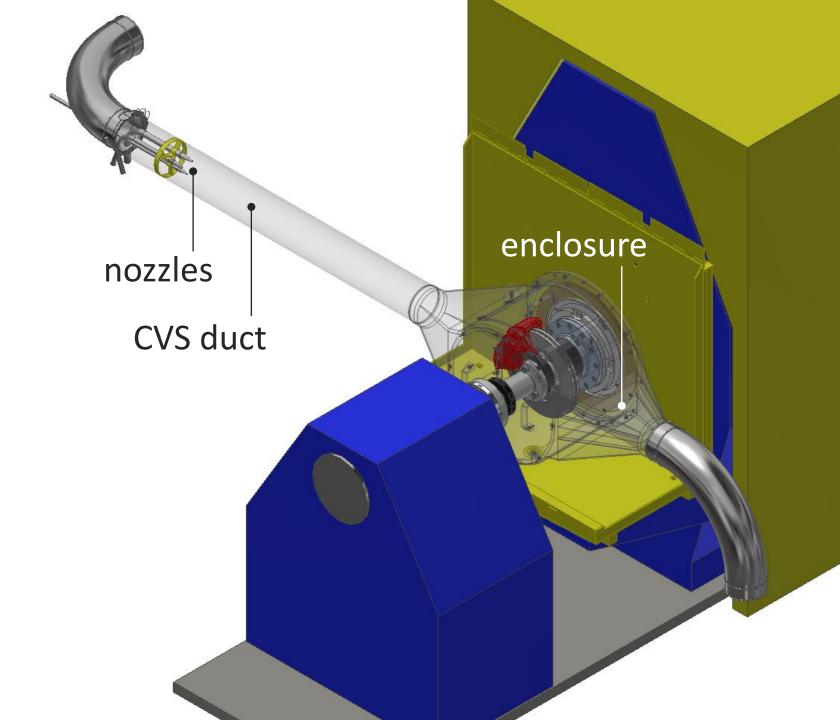
Design of **Experiments** 



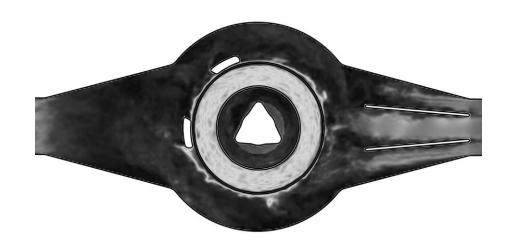
**Computational Fluid Dynamics** 

### DOE + CFD

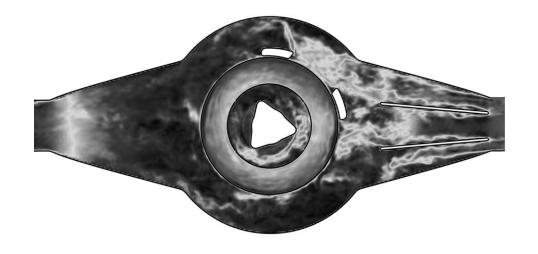
two powerful and efficient tools when used together, applied in three sections



airflow levels based on cooling air adjustment

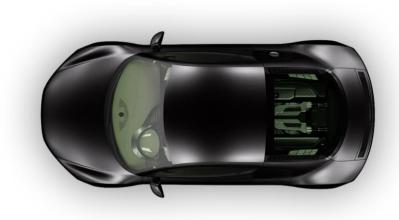


400 m³/h



1000 m<sup>3</sup>/h

brake size for midsize sedan and SUV



medium

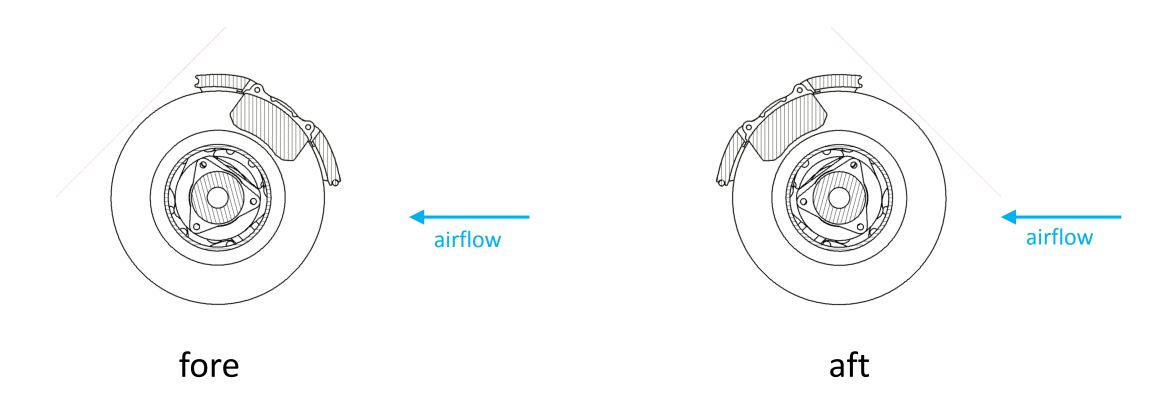


large

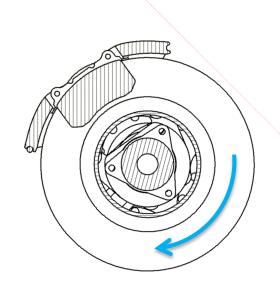
rotor design with influence on cooling and airflow pattern



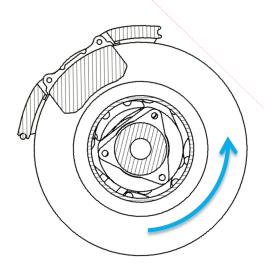
caliper orientation relative to incoming airflow



brake rotation direction from the dynamometer motor side

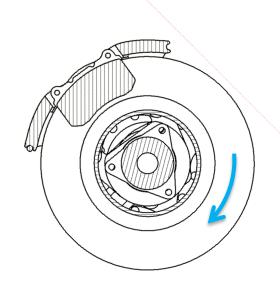


clockwise

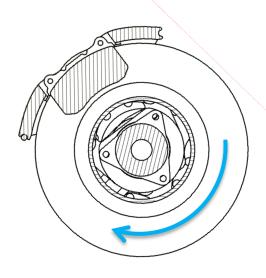


counterclockwise

brake rotational speed based on average brake size and WLTP-Brake cycle



400 RPM



900 RPM

fixture style from legacy performance and new emissions dyno



#### **DOE + brake enclosure**

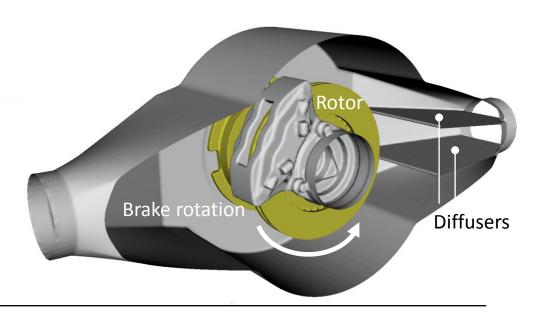
Simulation details

– Time step size: 20 μs

Grid spacing: 0.125"

Grid size: 384x192x144 (10.6 M grid points)

Each simulation was run on Flux
 (UM super computer) using 256 cores for 48 hours

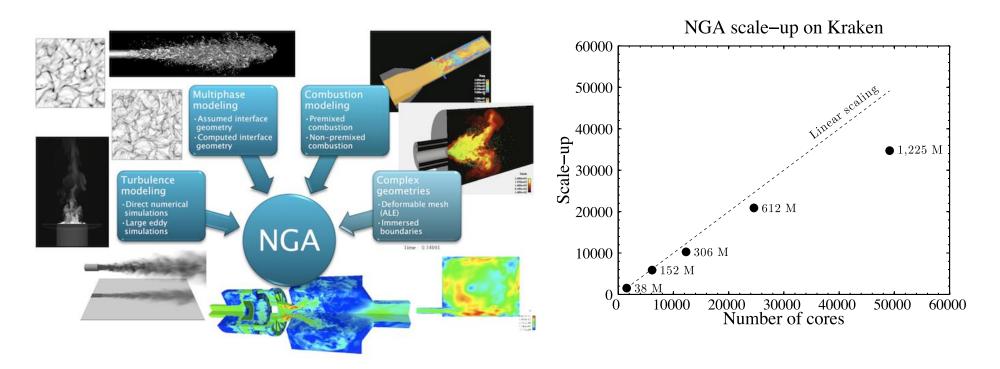


Run	Airflow	Brake size	Rotor design	Caliper orientation	Brake rotation	Brake speed	Fixture
1	400 m <sup>3</sup> /h	Small	Solid	Aft	CCW	900 rpm	Post
2	400 m <sup>3</sup> /h	Large	Solid	Fore	CCW	400 rpm	Knuckle
3	1000 m <sup>3</sup> /h	Large	Vented	Aft	CCW	900 rpm	Knuckle
4	400 m <sup>3</sup> /h	Large	Vented	Fore	CW	900 rpm	Post
5	1000 m <sup>3</sup> /h	Small	Solid	Fore	CW	900 rpm	Knuckle
6	1000 m <sup>3</sup> /h	Large	Solid	Aft	CW	400 rpm	Post
7	400 m <sup>3</sup> /h	Small	Vented	Aft	CW	400 rpm	Knuckle
8	1000 m <sup>3</sup> /h	Small	Vented	Fore	CCW	400 rpm	Post

## computational framework

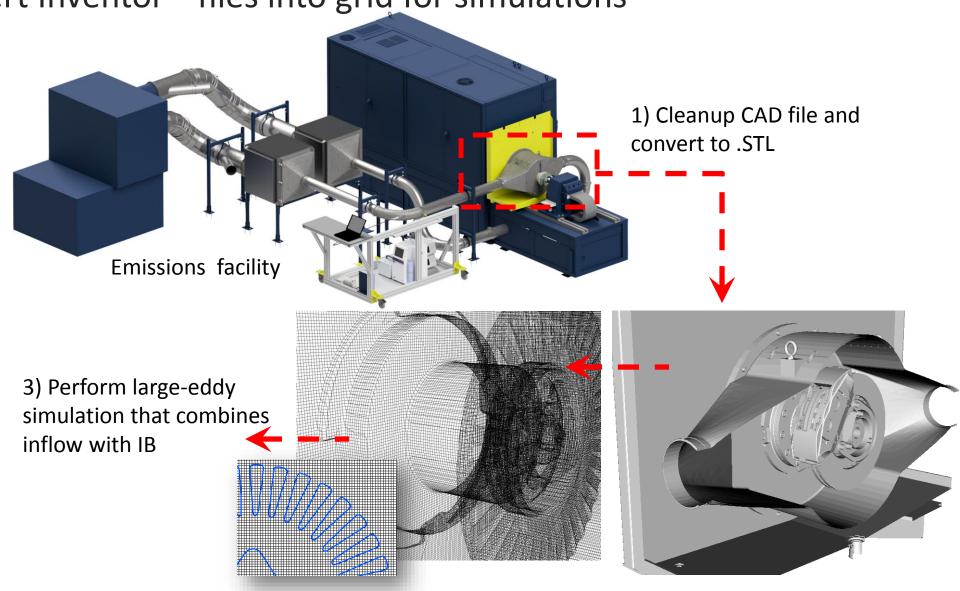
#### $NGA^{1,2}$

- Arbitrarily high-order multi-physics code
- Complex geometries handled efficiently using immersed boundaries
- Can simulate upwards of  $O(10^8)$  particles that explicitly captures collisions and mass/momentum/heat transfer between the phases



# main approach

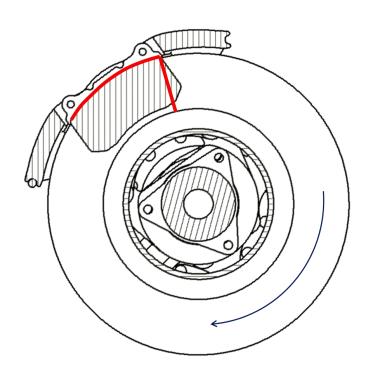
to convert Inventor™ files into grid for simulations

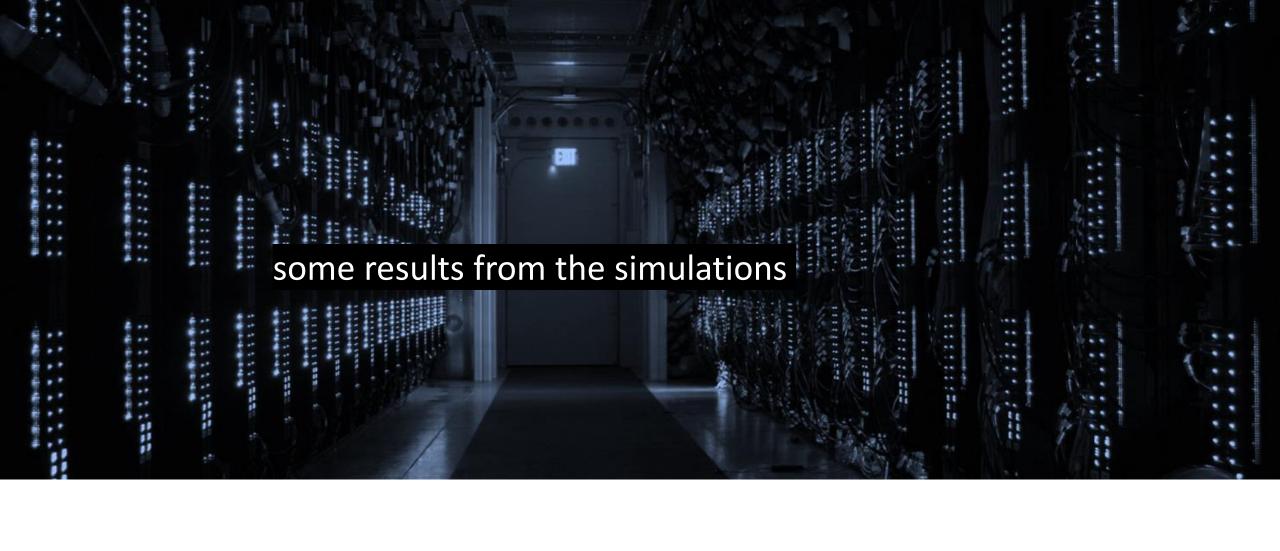


2) Automatic mesh generation using immersed boundaries (IB)

# **Inception lines**

nominal lines along which the emissions 'enter' the system



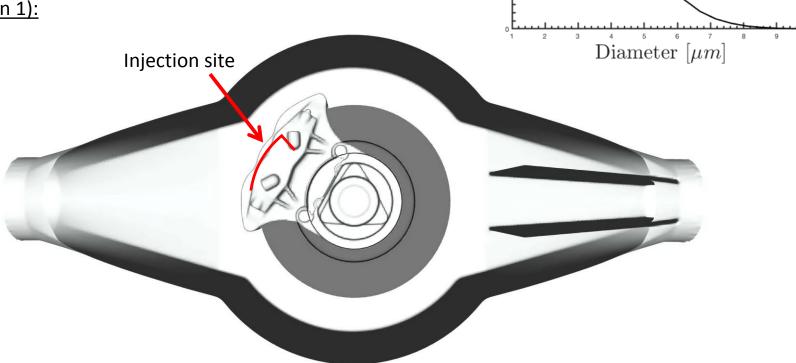


# particle inception

Particles are injected with prescribed size distribution

- Arizona road dust
- Mean particle diameter (by number) :  $0.917 \mu m$
- Standard deviation: 1.125
- Particle inception rate: 0.00925 μg/s

#### Example (Run 1):



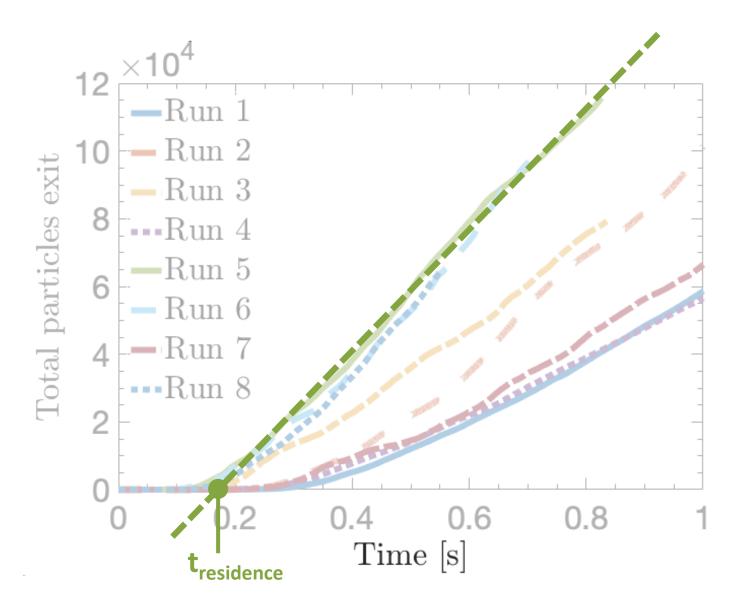
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PDF

Particle Size Distribution (by mass)

#### residence time

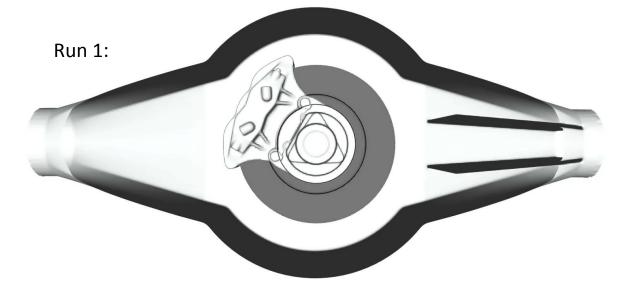
regression intercept to represent time it takes for particles to reach the exit plane



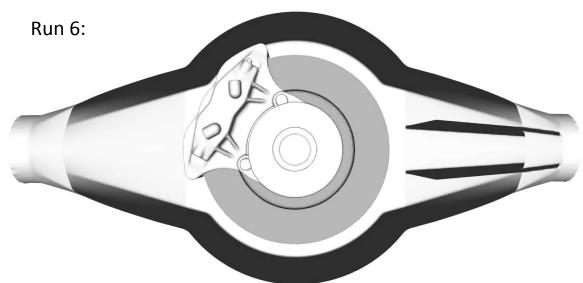
# particle transport

NGA codes tracks each particle individually

400 m³/h
Small brake
Solid disc
Aft position
CCW rotation
900 RPM
Post fixture

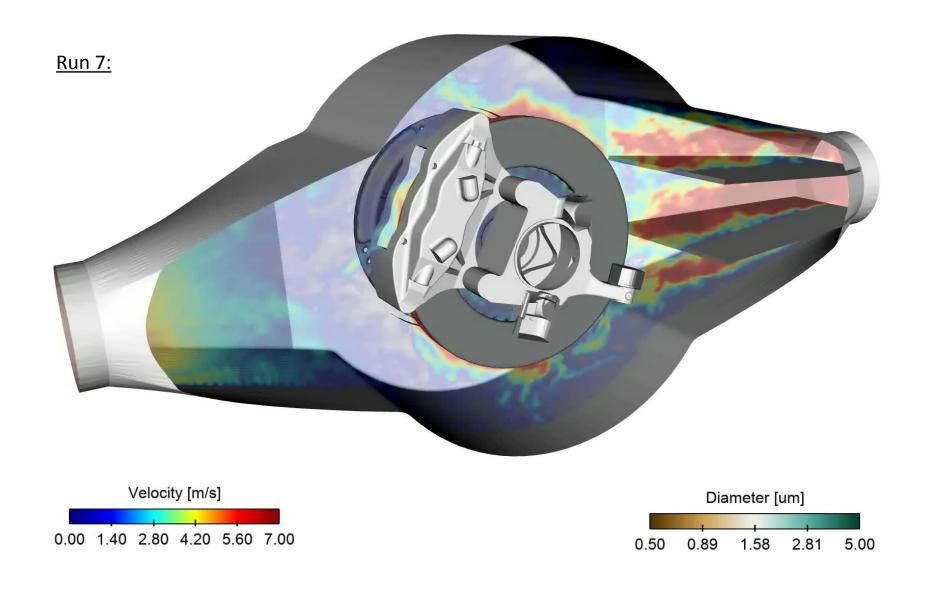


1000 m³/h
Large brake
Solid disc
Aft position
CW rotation
400 RPM
Post fixture



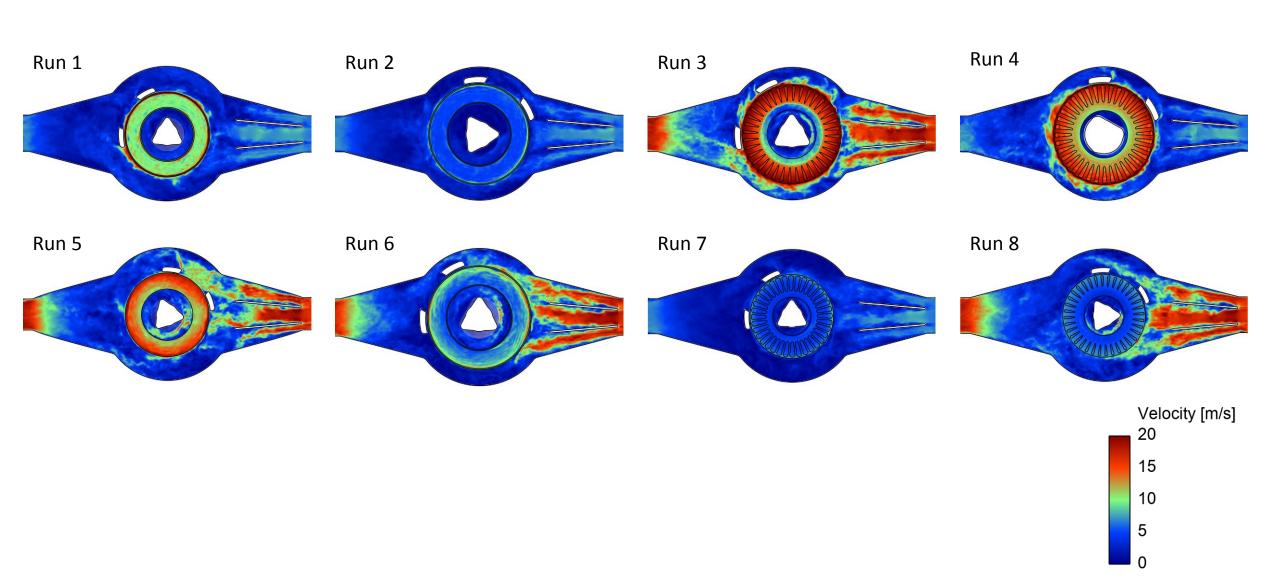
# ...particle transport

full visualization of air speed behavior and particle response within enclosure



# instantaneous velocity profiles

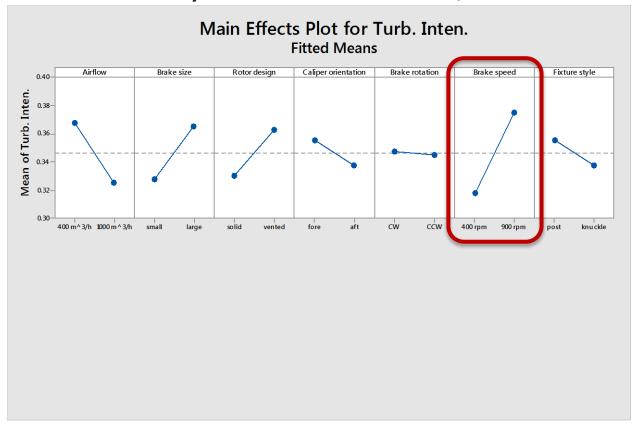
full visualization of air speed behavior and particle response within enclosure

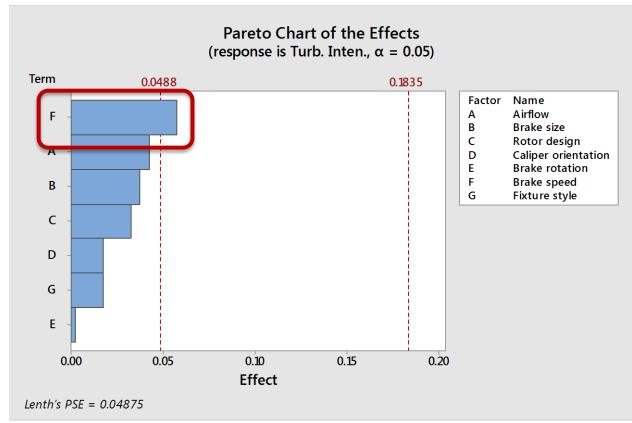


With two metrics for enclosure behavior and two for particle charactistics

Metric	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
Turbulence intensity	0.358	0.344	0.374	0.447	0.323	0.301	0.325	0.315
Particle res. Time / s	0.40	0.35	0.22	0.35	0.17	0.20	0.37	0.23
D <sub>50</sub> @ exit / μm 0.8588	0.8373	0.8523	0.8380	0.8419	0.8498	0.8546	0.08552	0.8597
D <sub>84</sub> @ exit / μm 1.916	1.797	1.863	1.797	1.832	1.868	1.903	1.893	1.931

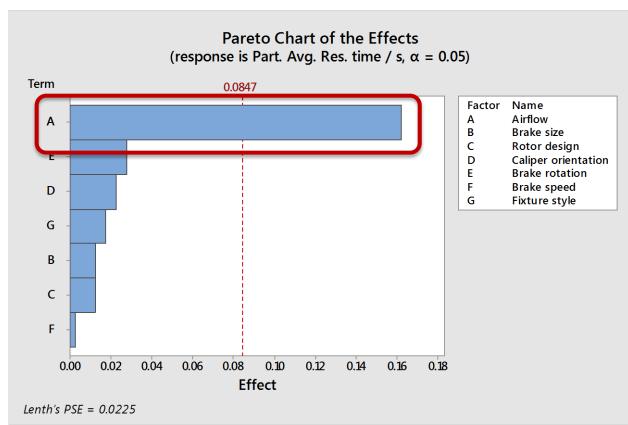
turbulence intensity is more sensible to brake speed (cycle), followed by the airflow level, and brake size



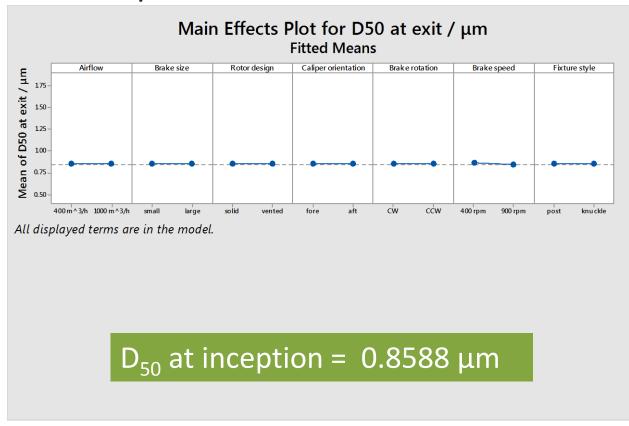


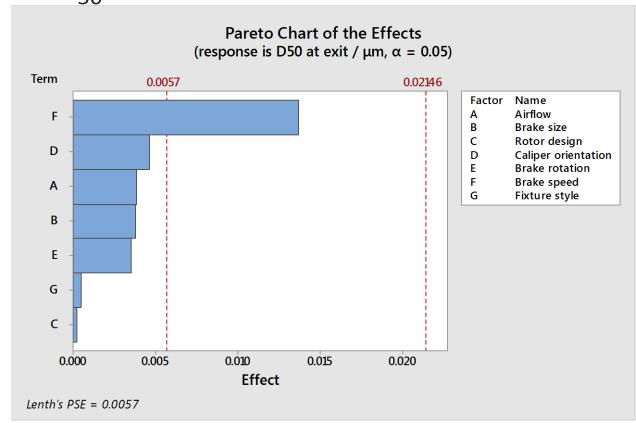
residence time is mainly determined by the airflow level



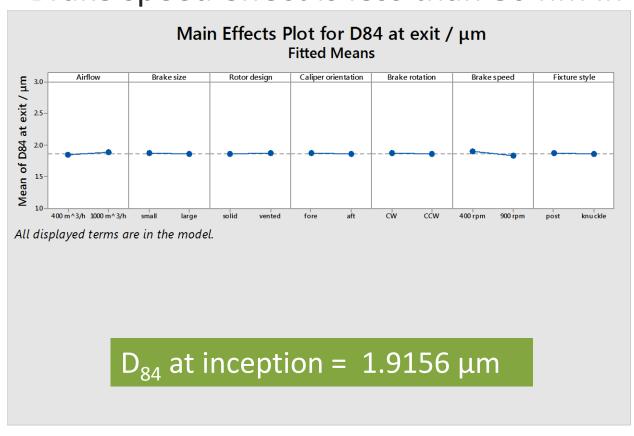


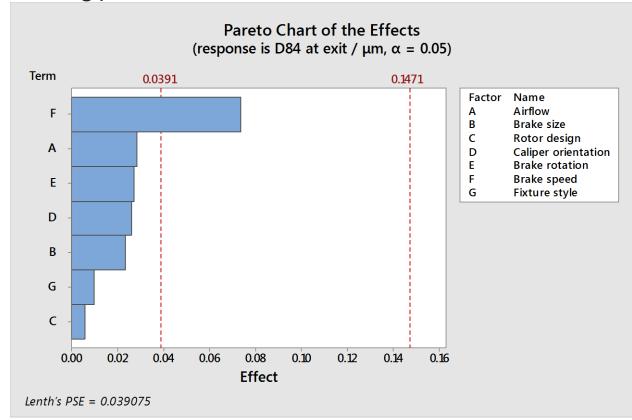
Particle size for 50% of range ( $D_{50}$ ) is stable for all factors Brake speed effect is less than 15 nm in the  $D_{50}$  variation





Particle size for 84% of range ( $D_{84}$ ) is stable for all factors Brake speed effect is less than 80 nm in the  $D_{84}$  variation



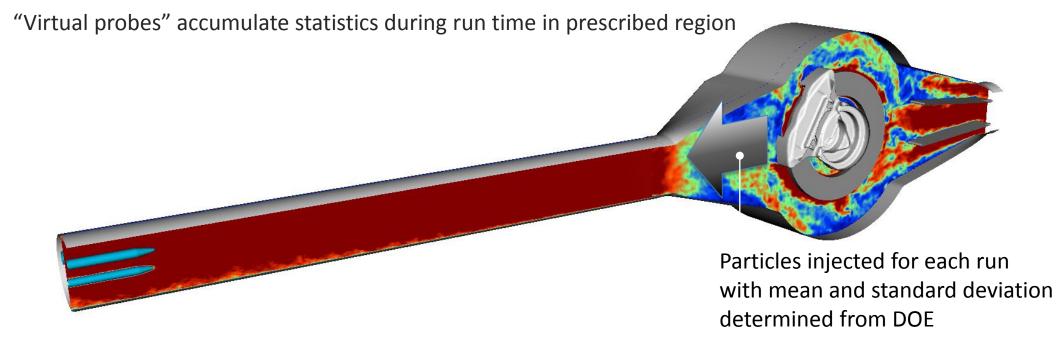


# particle size measurement transport

full visualization of air speed behavior and particle response within enclosure

#### <u>Simulation features:</u>

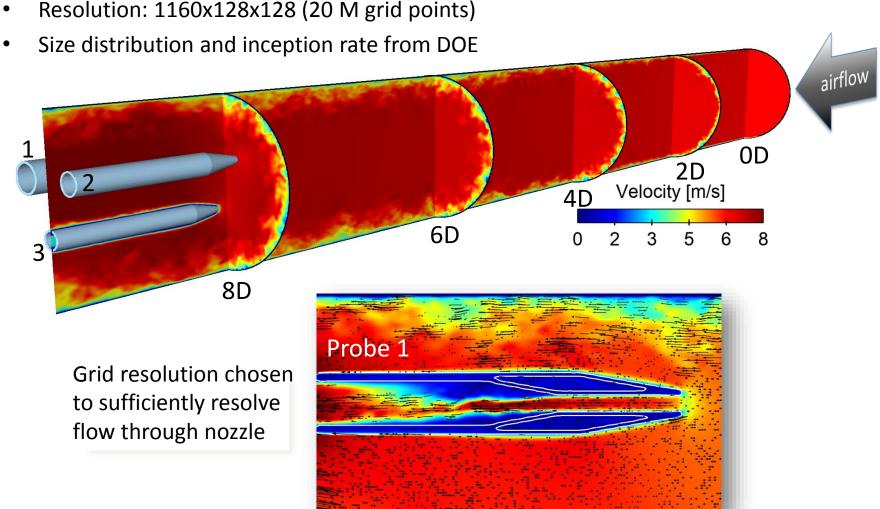
- Large-eddy simulation to capture high-Reynolds number flows
- Cut-cell immersed boundary for sharp representation of complex geometry
- Direct-forcing immersed boundary for moving surfaces and thin walls
- Lagrangian particle tracking for realistic particulate measurements



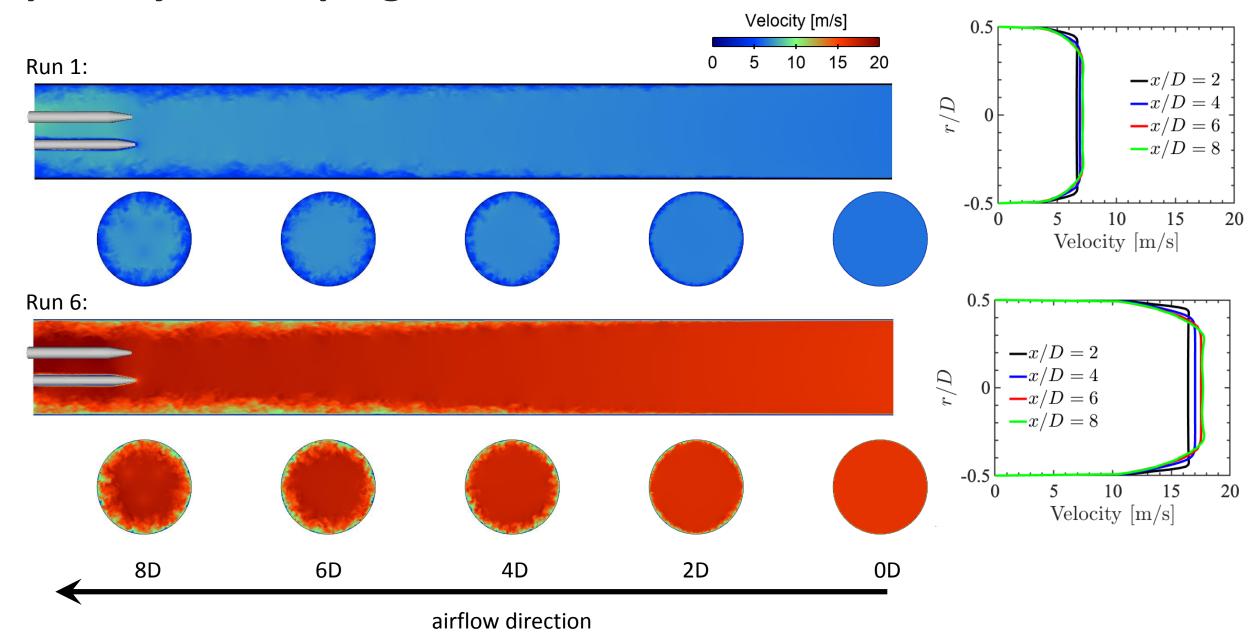
#### Airflow behavior inside CSV duct

full visualization of air speed behavior at four different distances

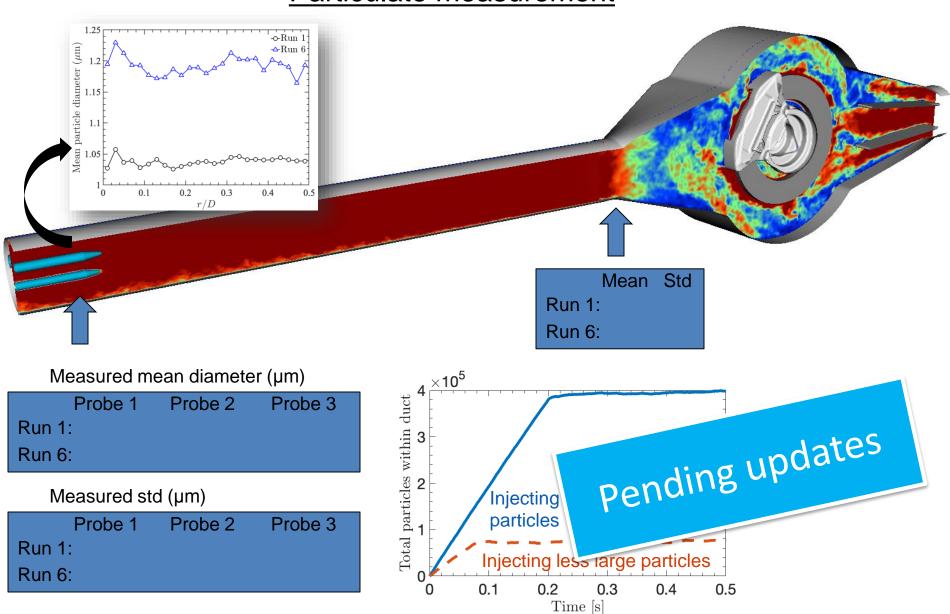
- Pipe simulation performed for Run 1 and Run 6
- Resolution: 1160x128x128 (20 M grid points)



# spatially developing duct flow



#### Particulate measurement



## ...in summary

CFD is more useful when using metrics

Airflow and brake speed are significant factors

High-fidelity CFD complements nicely other tools



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