3D-CFD-Simulations of the gas-particle flow in a cold gas Laval nozzle to predict the mechanical erosion

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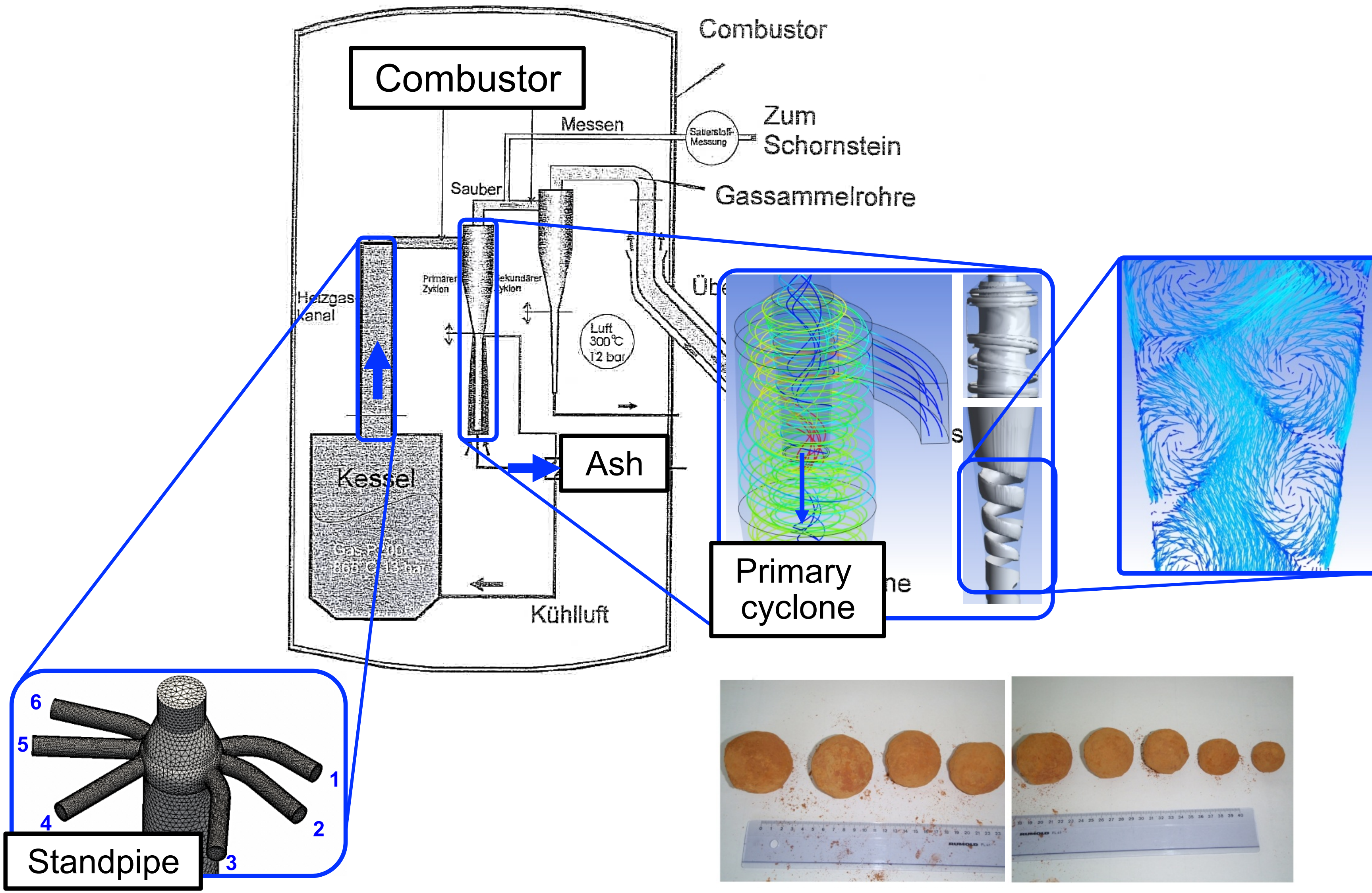
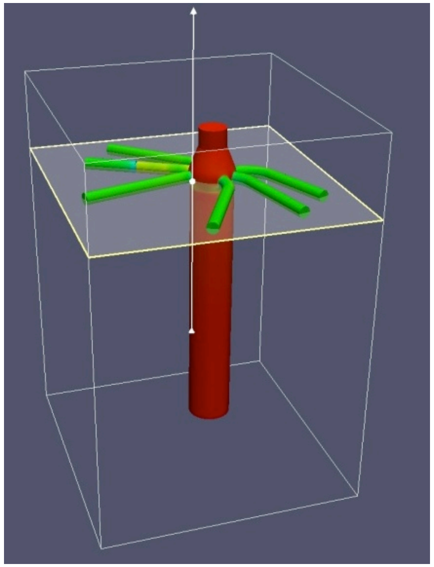
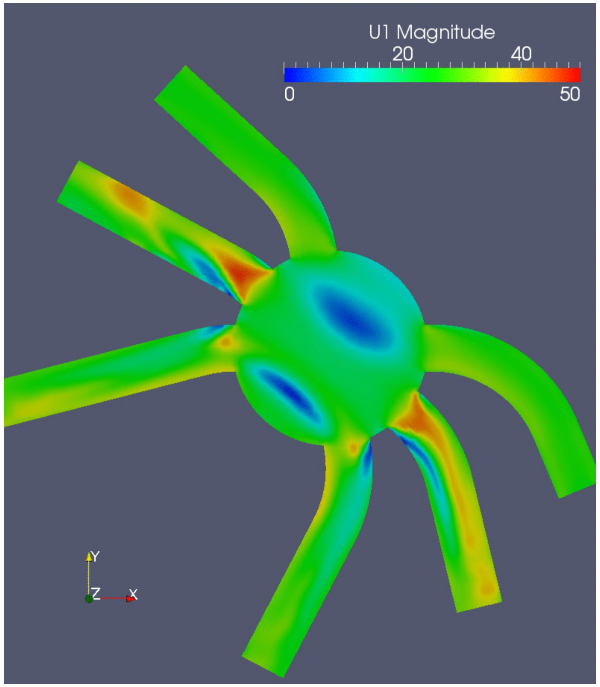
3D CFD of multiphase flows in power plants at CHP Cottbus as an example

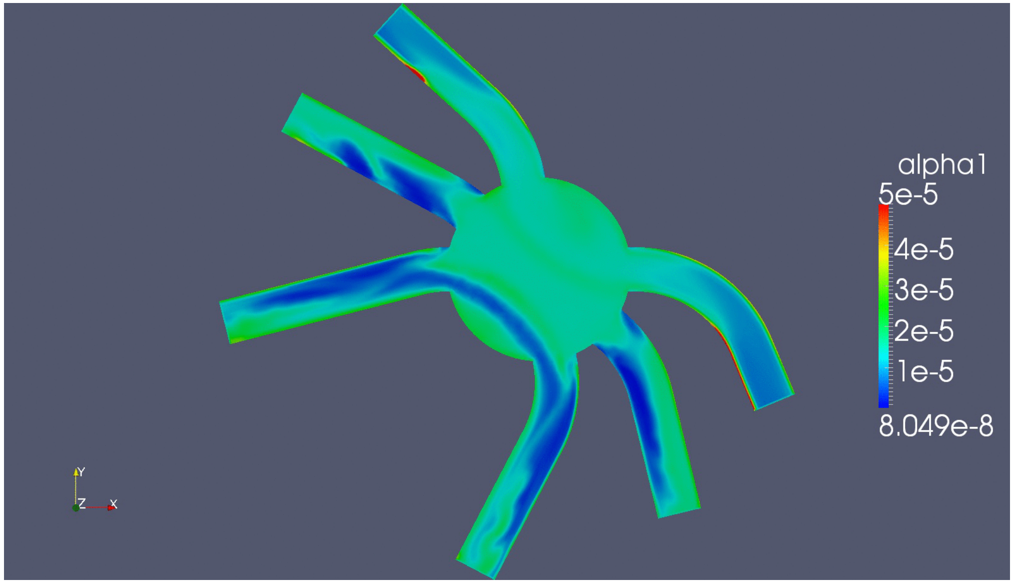


3D CFD of multiphase flows in power plants at CHP Cottbus as an example

- Prediction of the two-phase flow in the standpipe
- Non homogeneous mass fluxes at the outlets
- Euler/Euler method

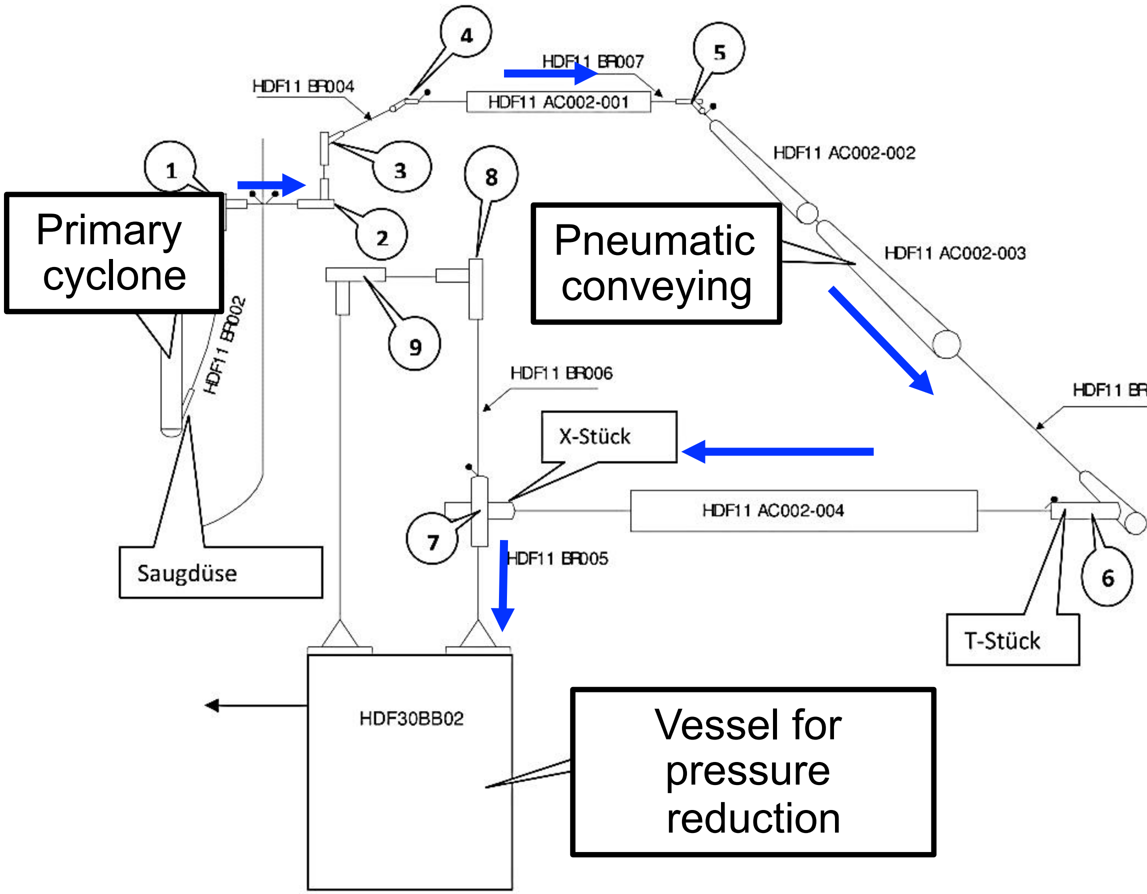


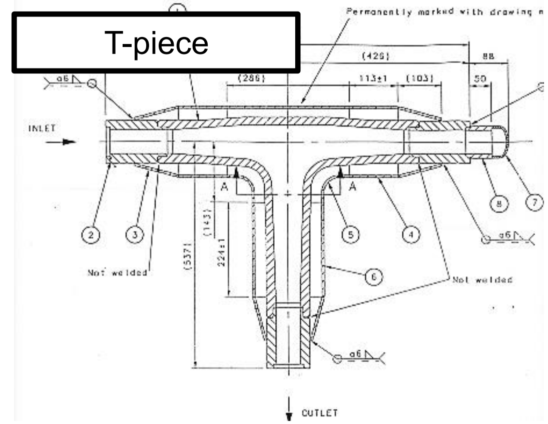




3D CFD of multiphase flows in power plants at CHP Cottbus as an example

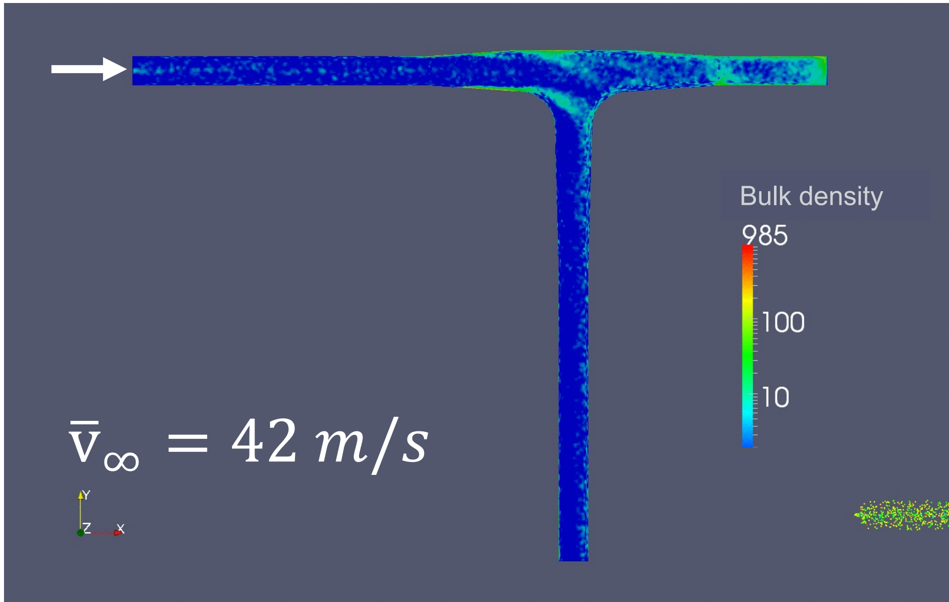
Overview of the pneumatic ash transport system:

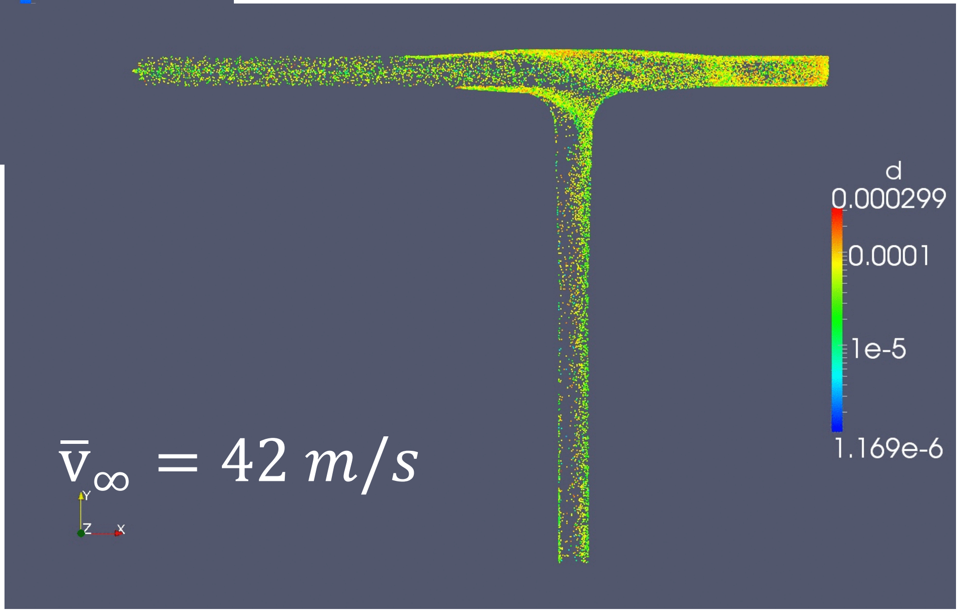




Numerical simulations in cooperation with the Cottbus power plant

Euler/Lagrange simulation at a T-piece





Numerical simulations in cooperation with the Cottbus power plant

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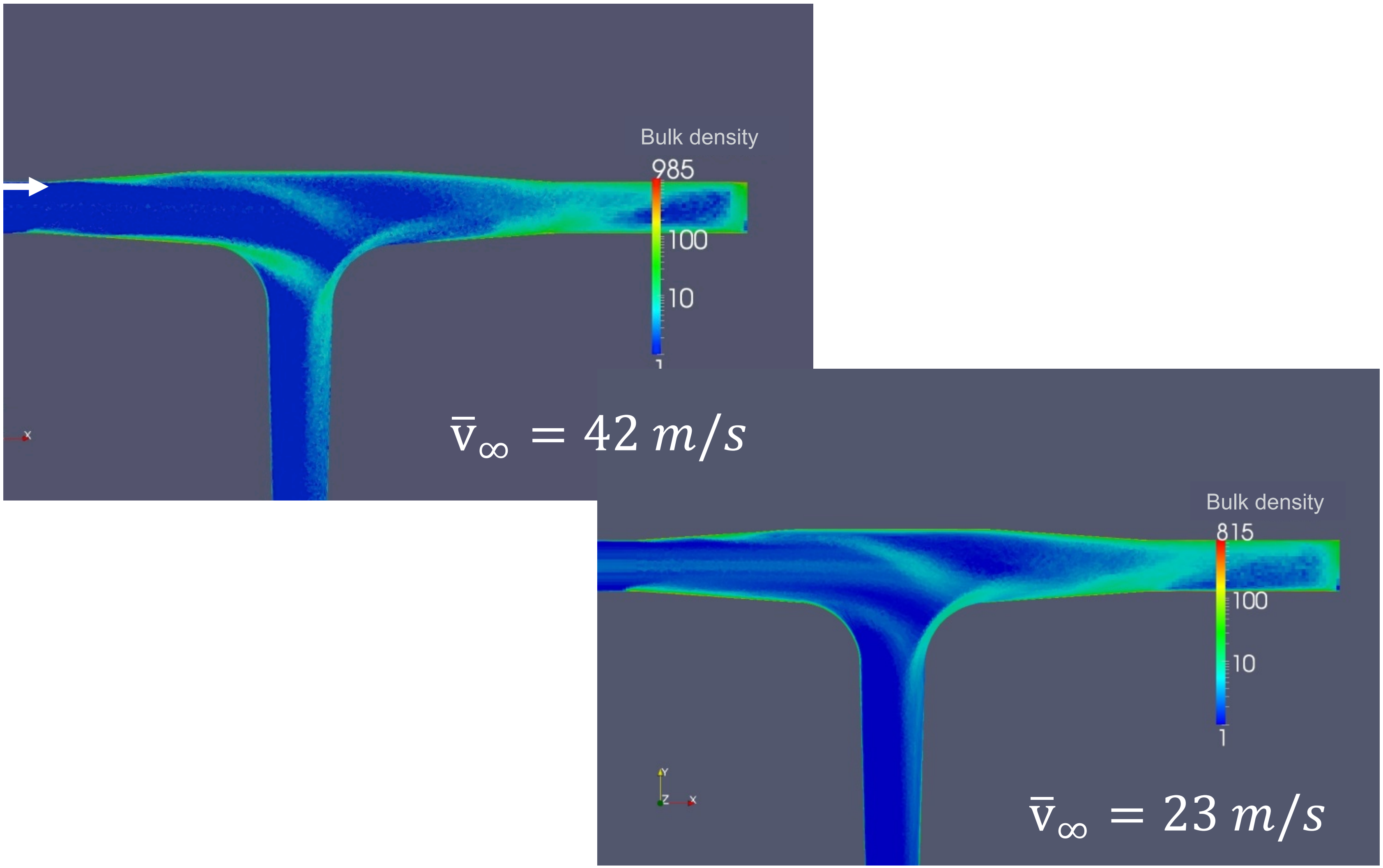
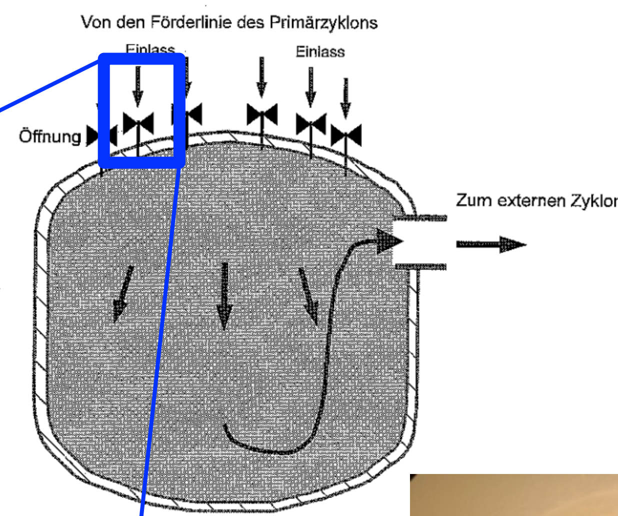
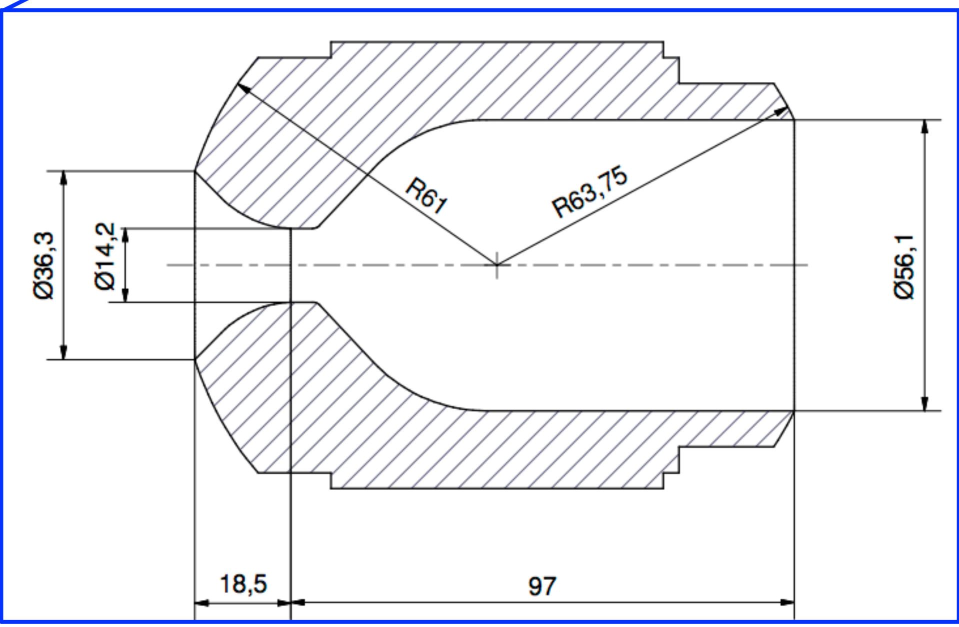
Time averaged:

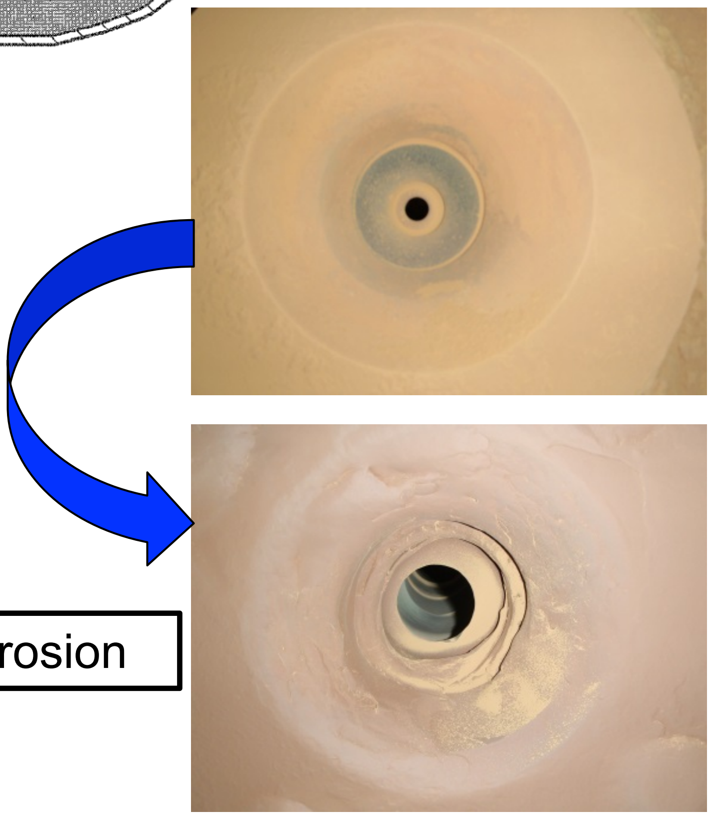


Motivation

Vessel for pressure reduction:







Erosion

Nomenclature

Added mass force	$\vec{F}_{AM}$
Density	ρ
Diameter	d
Diffusive flux of heat	$\vec{j}$
Drag Force	$\vec{F}_D$
Dynamic viscosity	μ
Mass	m
Momentum source due to particle forces	$\vec{S}$
Pressure	p
Pressure gradient force	$\vec{F}_{PG}$
Speed of sound	c
Temperature	T
Volume	V
Velocity	$\vec{v}$
Viscous stress Tensor	T
Work due to particle forces	W

Volume fraction of the particle phase	$\alpha_p = \frac{V_p}{V}$
Bulk density	$\rho_b = \alpha_p \cdot \rho_p$
Mach number	$Ma = \frac{\lvert\vec{v}\rvert}{c}$
Mass load	$\mu = \frac{m_p}{m_c}$
Particle response time	$\tau_p = \frac{\rho_p d_p^2}{18 \mu f_D}$
Reynolds number	$Re = \frac{\lvert\vec{v}\rvert \cdot d \cdot \rho_c}{\mu}$
Stokes number	$St = \frac{\tau_p \lvert\vec{v}\rvert}{d}$

Subscript

Inlet condition	∞
Particle phase	p
Continuous phase	c

State of the art

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<u>Particle tracking in a Laval nozzle</u>

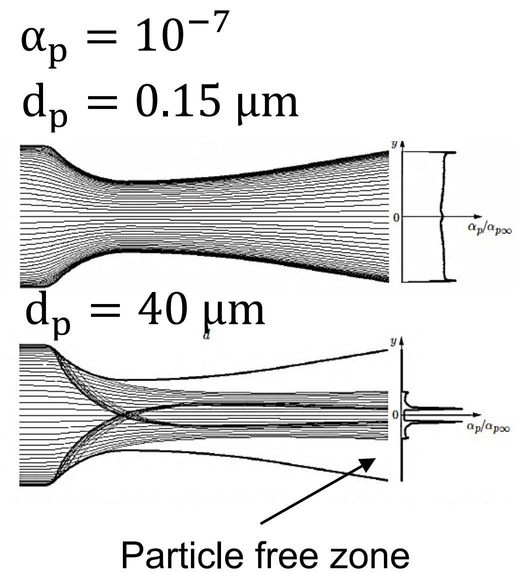
- Exp: Lu et al. 2011
  - showed that the flow through a Laval nozzle is less sensitive to the gas flow rate and pressure disturbances

  → made it easier to control coal mass flow rate precisely
- Num: Verevkin, Tsirkunov. 2008
  - Increasing Stokes number → higher particle inertia
  - Separation from streamlines → Particle free zone

    →Number of colliding particles increases

    →Higher momentum of impacting particles

    →Large particle concentrates around centerline



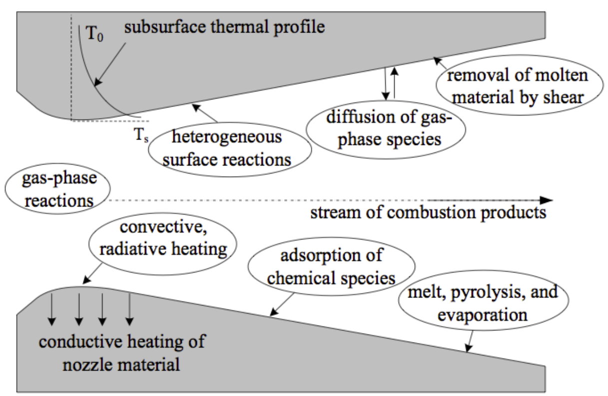
Lu et al. 2011. *Flow characteristics and pressure drop across the Laval nozzle in dense phase pneumatic conveying of the pulverized coal*. Chemical Engineering and Processing, 50

Verevkin, Tsirkunov. 2008. *Flow of a dispersed phase in the Laval nozzle and in the test section of a two-phase hypersonic shock tunnel*. Journal of Applied Mechanics and Technical Physics, 49

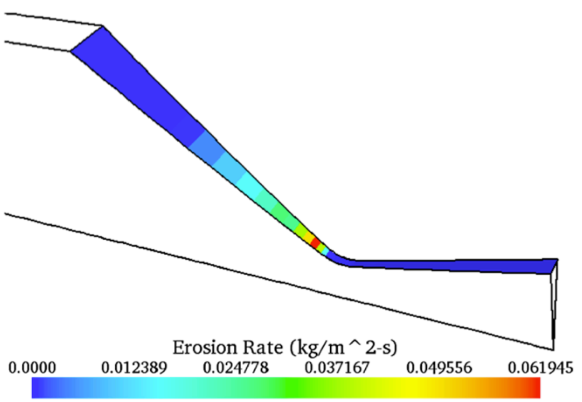
State of the art

Erosion due to particles impacts in a Laval nozzle

- Num: Thakre. 2008
  - Mechanical erosion caused by the impingement of particles is negligible in the throat region, it is not significant to total mass loss
- Num: Thakre et al. 2013
  - Mechanical erosion is prevalent only in the convergent section of the rocket nozzle



$d_p = 50..80$ µm, $\mu = 0.006..0.08$



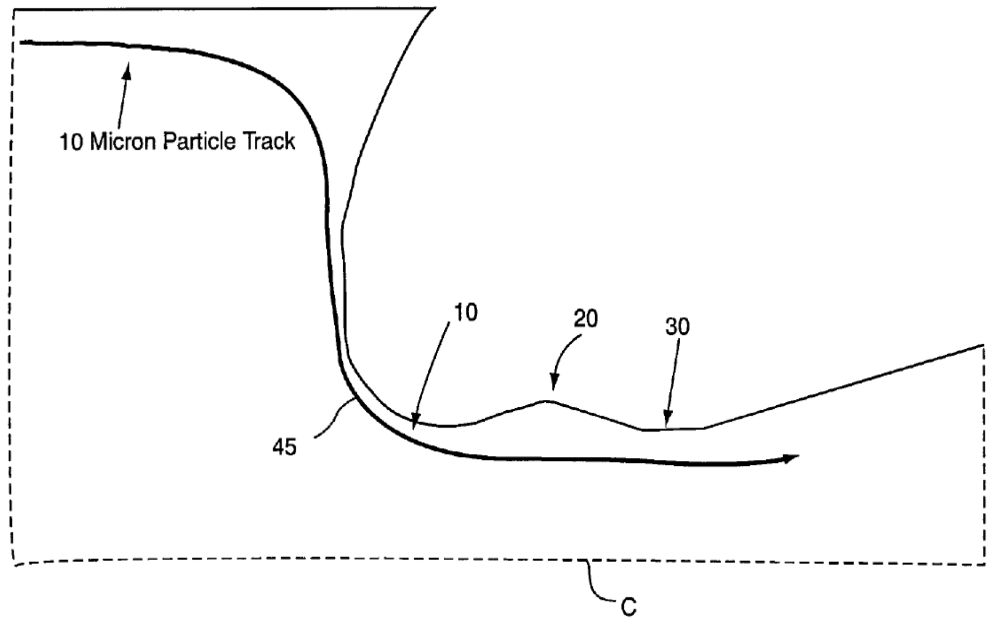
Thakre. 2008. *Chemical erosion of graphite and refractory metal nozzles and its migation in solid-propellant rocket motor.* Thesis

Thakre et al. 2013. *Mechanical erosion of graphite nozzle in solid-propellant rocket motor.* Journal of Propulsion and Power, 29

State of the art

Optimized shape

- Num: Hennessey. 2001

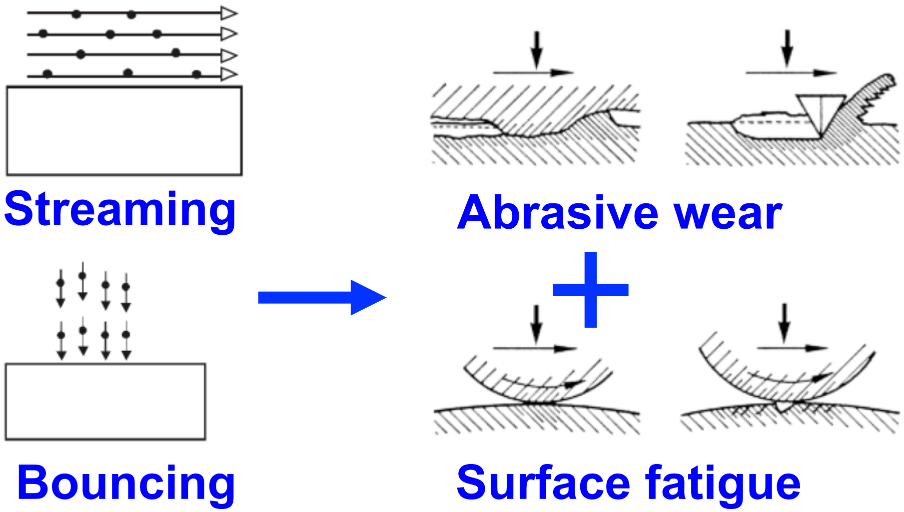


→ Flow predictions of Laval nozzles are usually performed for rocket nozzles

- Different conditions like temperatures up to 3000 K
- Reacting and/or melting particles
- Main erosion in these cases is due to chemical erosion and melting surfaces whereas mechanical erosion is neglected
- Furthermore the lifetime of such nozzles is in the order of minutes compared to thousands of hours in our case.

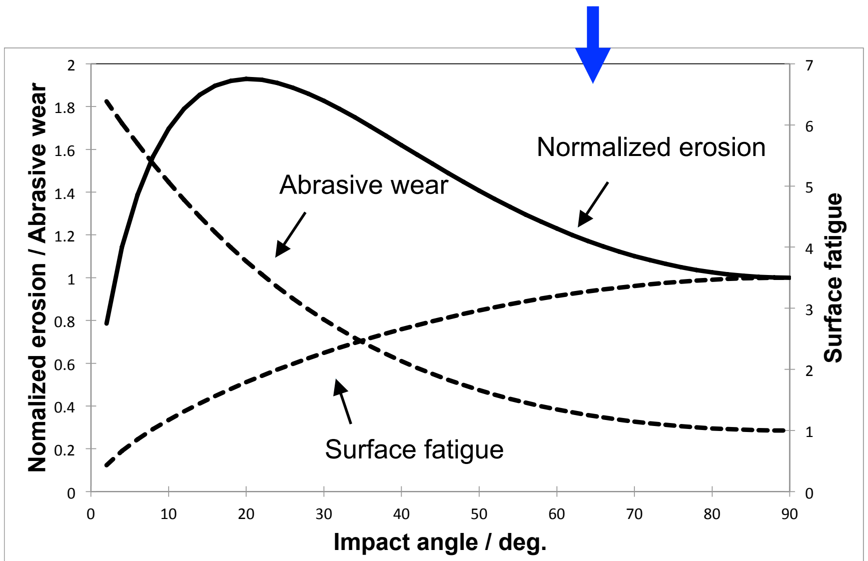
Hennessey. 2001. *Erosion resistant rocket nozzle*, US Patent 6330793

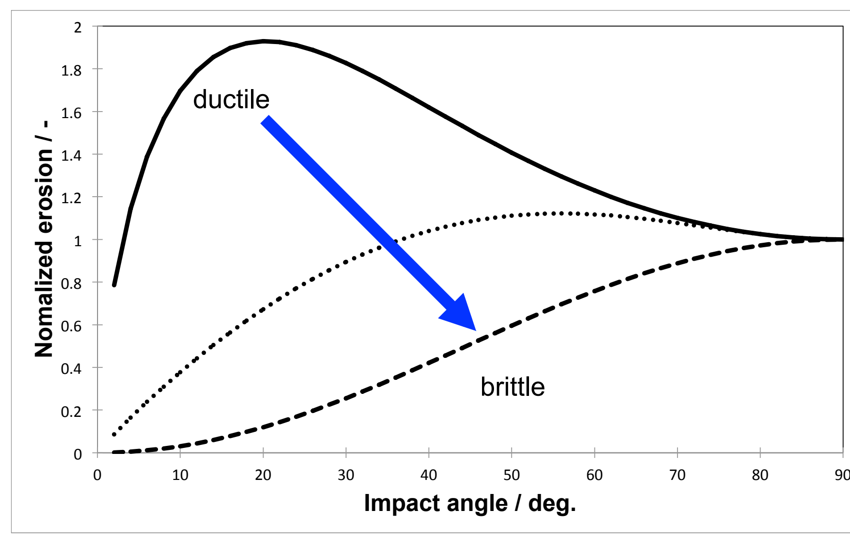
Dominant wear mechanisms



Depends on material:

- ductile cutting and plastic deformation
- brittle fracture





Sommer et al. *Verschleiß metallischer Werkstoffe*. Vieweg+ Teubner (2014).

Numerical methods

- Open source software package OpenFOAM
- Density based compressible solver rhoCentralFoam
  - does not involve Riemann solver
  - based on central-upwind schemes

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0$$

$\neq 0$ for 2/4-way-coupling

$$\frac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot [\vec{u}(\rho \vec{u})^T] + \nabla \mathrm{p} + \nabla \cdot T = \vec{S}$$

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot [\vec{u}(\rho E)] + \nabla \cdot (\mathrm{p}\vec{u}) + \nabla \cdot (T \cdot \vec{u}) + \nabla \cdot \vec{j} = W$$

Weller et al. 1998. *A tensorial approach to computational continuum mechanics using object-oriented techniques*. Computers in Physics, 12

Greenshields et al. 2009. *Implementation of semi-discrete, non-staggered central schemes in a colocated, polyhedral, finite volume framework, for high-speed viscous flows*. Int. J. Numer. Meth. Fluids

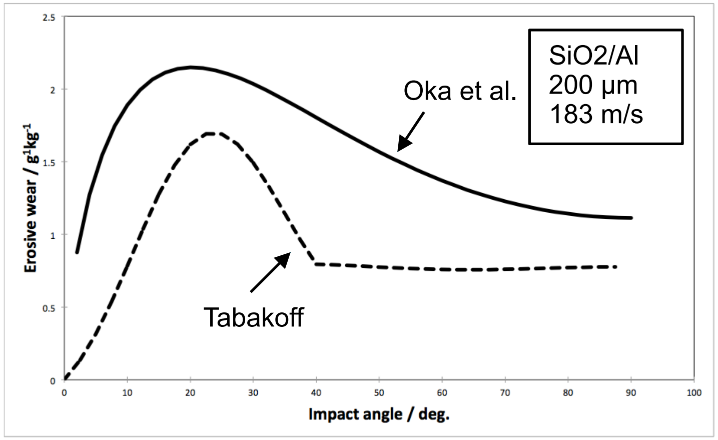
Marcantoni et al. 2012. *High speed flow simulations using OpenFOAM*. Mecánica Computacional, 2012

Numerical methods

- Combination of the compressible solver with particle methods supplied by OpenFOAM → Euler/Lagrangian coupling
- Equation of motion

$$m_p \frac{d\vec{v}_p}{dt} = \vec{F}_D + \vec{F}_{PG} + \vec{F}_{AM}$$

- Drag force by Henderson, takes high Mach number into account
- Stochastic Particle-Wall collisions
- Erosion modeling by Tabakoff



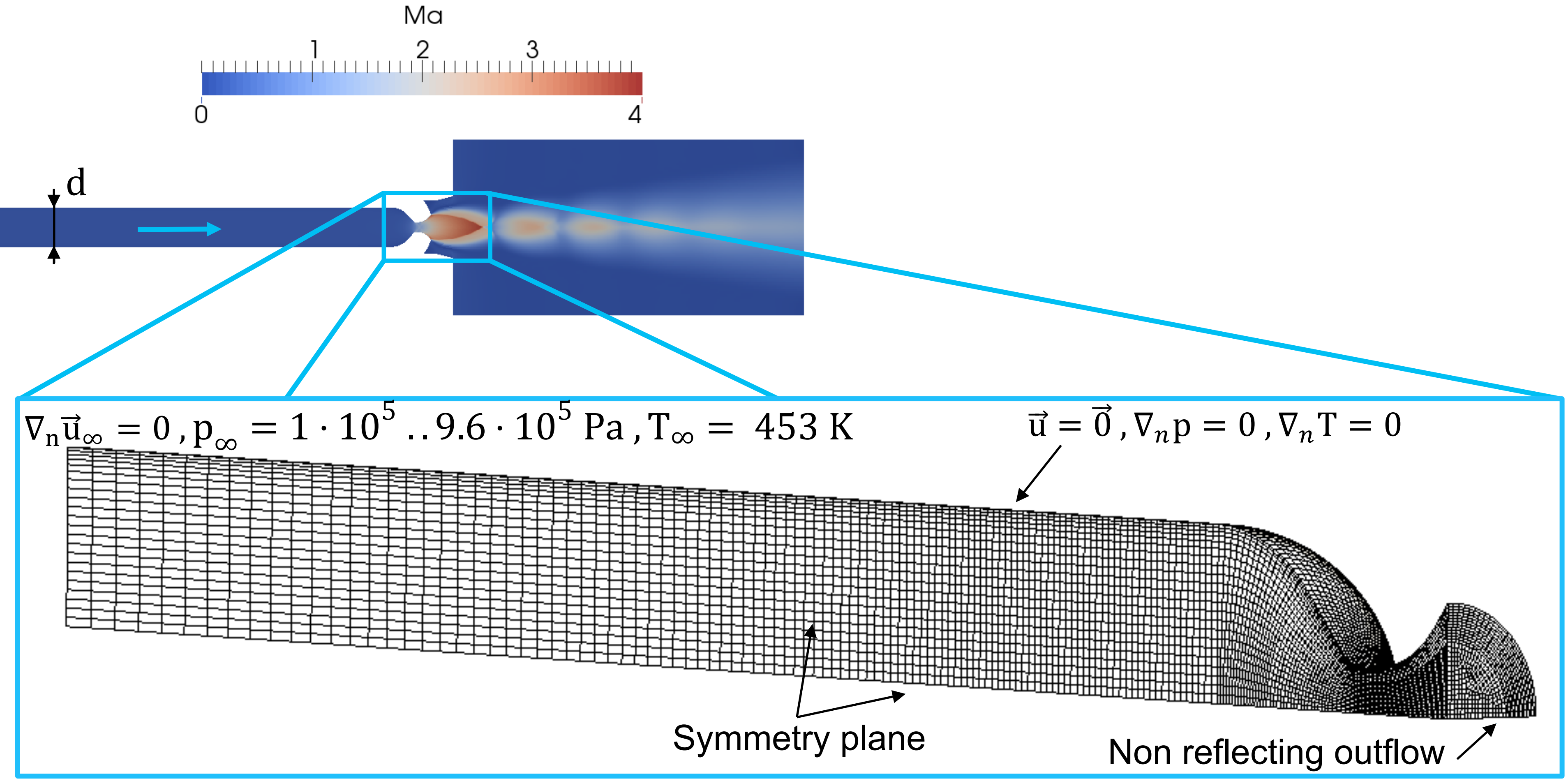
Sommerfeld, Huber. 1999. *Experimental analysis and modelling of particle-wall collision*. International Journal of Multiphase Flow, 25

Henderson. 1976. Drag coefficients of spheres in continuum and rarefied flows. AIAA Journal, 14

Grant, Tabakoff. 1975. *Erosion prediction in turbomachinery resulting from environmental solid particles*. J. Aircraft, 12

Oka et al. 2005. *Practical estimation of erosion damage caused by solid particle impact part 1&2*. Wear, 259

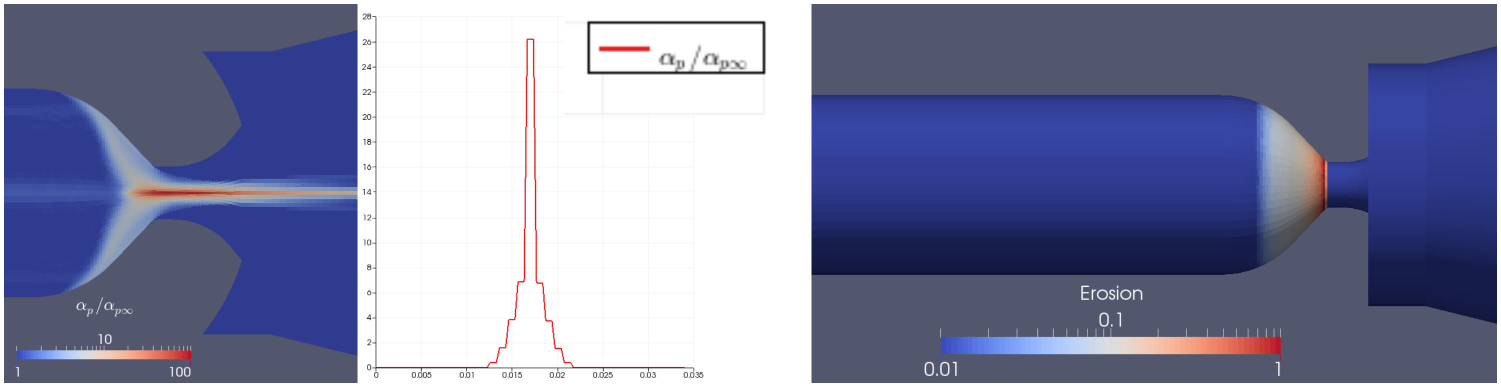
Numerical set-up



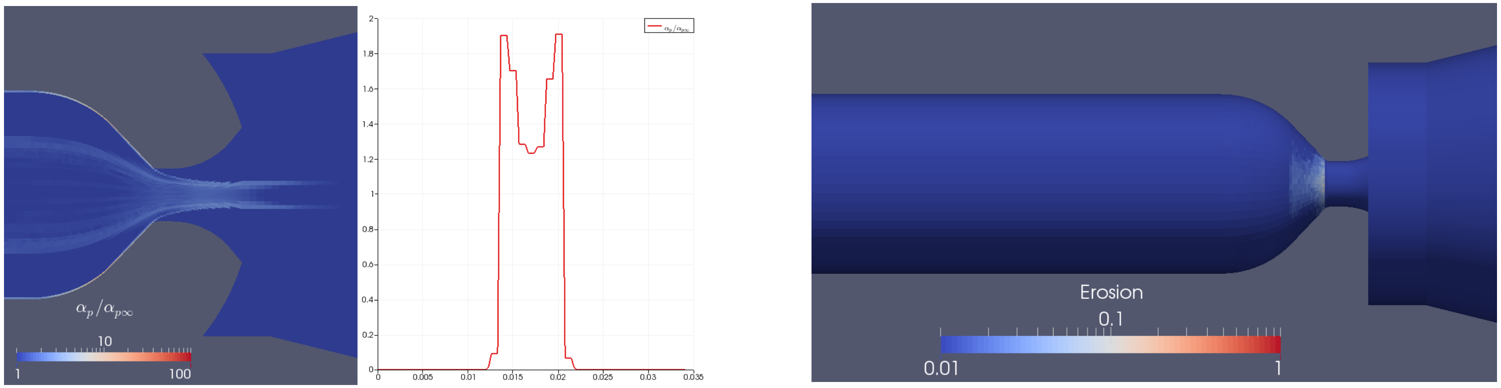
- 72716 cells
- Time step according to CFL < 0.25
- SST k-ω turbulence model
- $Re_\infty \sim 300{,}000$
- $\mu = 0.3$
- $d_p = 1,10,100\ \mu m$
- $\rho_p = 2500\ kg/m^3$
- 1e7 parcels per second, 220,000 at once
- 1 way coupling

Results/Qualitive comparison

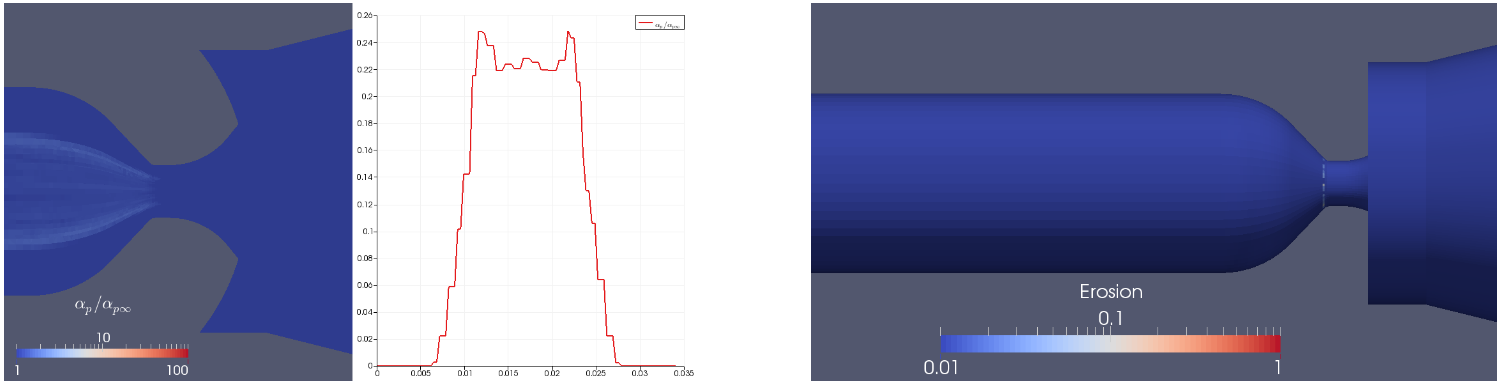
100 µm,
St = 97



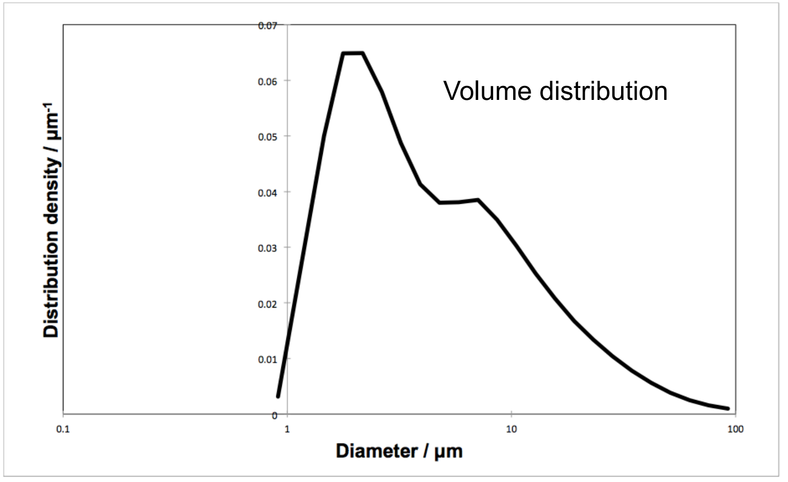
10 µm,
St = 3

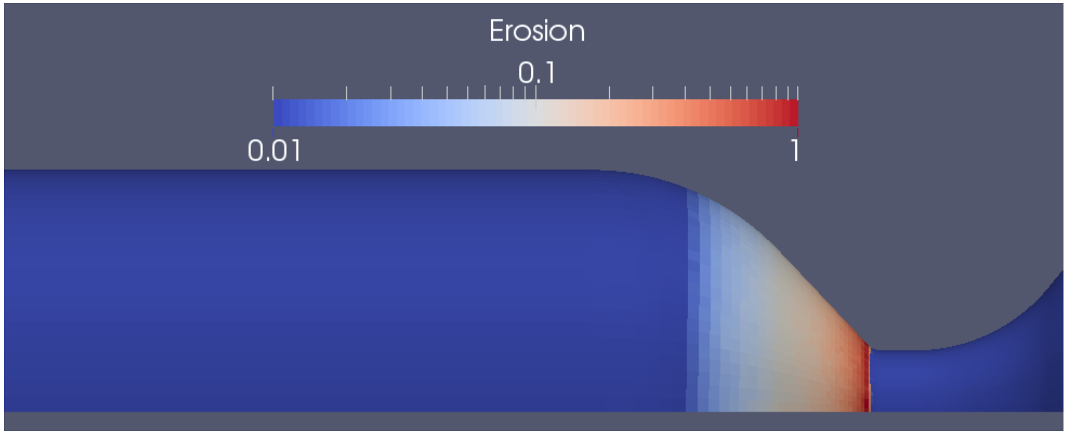


1 µm,
St = 0.05



Results/Qualitive comparison





- It could be observed that particles with St > 1 strongly tended to collide with the nozzle wall
- Erosion mainly due to the largest particles
- Erosion located in a small area in front of the throat
- Qualitatively comparable with numerical and experimental research of two phase flow Laval nozzles

Outlook

- Two-way and four-way coupling is necessary to achieve more accurate results
- particle-particle collisions will be modeled by the stochastic method of O'Rourke
- Modification of the Navier-Stokes equation which takes dispersed phase volume fraction into account
- Verification:
    - Quantitive comparison with pressure drop according to Lu et al. 2011
    - Comparison of the predicted erosion with Thakre et al. 2013
- Variation of geometry, material and mass load

Amsden et al. 1989. *KIVA-II: A computer program for chemically reactive flows with sprays.*

Thank you for your attention.