Numerical and Experimental Investigation of the Plasma Down Stream Reactor

Master Thesis

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Project Background

- Cohesive powders cause many problems in the chemical & pharmaceutical industry
  - Conveyance
  - Mixing
  - Bottling
- Reason: Interparticle forces
- We **improve the flow behavior of cohesive powders** by reducing these forces
Principle: Nanoparticle Deposition

- Van der Waals Force according Hamaker

\[ F_{\text{VdW}} = \frac{A}{12} \cdot \frac{R}{H^2} \]

- Increasing the distance between the particles by a surface deposition

\[ H_{\text{min}} = 4 \cdot 10^{-10} \text{ m} \]
\[ A = 3 \cdot 10^{-20} \text{ J} \]
Plasma Down Stream Reactor

- Defined short residence time (< 0.1 s)
- Continuous treatment possible
- Patented Setup
Nanoparticle Deposition in the Plasma

- Process to build $\text{SiO}_x$ Nanostructure on the substrate particle surface
Motivation for the Master Thesis

- Problem:

- Implications:
  - Chemical degradation or melting of temperature sensitive particles
  - Blockage of the reactor → no continuous operation

- Goals:
  - Investigation of the: — heat fluxes — temperature profile — particle temperature
  - Numerical model of the particle-wall interaction → Avoid adhesion

Adhesion at the walls
Numerical Model Definition

- 2D model
- Particle-wall interaction
  - Contact & Damping forces
  - Van der Waals force
- Particle path without contact
  - Coulomb force
  - Fluid drag force
  - Ion drag force
- Qualitative statements
Particle-Wall Contact

- Adhesion depends on the normal velocity

Reflection:
Normal contact force is higher than the van der Waals force

Equilibrium between the van der Waals force and the normal contact force

\[ d_p = 5.5 \, \mu m \]
Particle-Wall Contact

- Dependency on the particle radius
  - normal velocity: 0.1 m/s

\[ d_p = 5.5 \mu m \]
Temperature Measurements

- Gas and wall temperature in the plasma zone
- Fiber-optic system
  - GaAs crystal with temperature dependent band gap displacement
  - Not influenced by electromagnetic fields
Sensor fixation

Inside the reactor

Outside wall
Temperatures in the Plasma

Heating due to ion bombardment

Loss due to radiation

Loss due to convection

→ No direct measurement possible
Calculation Procedure

- Sensor temperature measurements
- Calculation of the heat fluxes

\[
\frac{dT_S}{dt} \cdot \frac{m_S \cdot c_{p,S}}{A_S} = \alpha \left( T_g - T_S \right) + \dot{Q}^{\text{plasma}} - C_s \cdot \varepsilon_s \left( T_S^4 - T_{w,in}^4 \right)
\]

- Heating due to the plasma
- Radiation
- Convection
- Calculation of the resulting particle temperature
Parameter Study in the Short Reactor

- Influence on the temperature propagation
  - Plasma forward power: 50, 75, 100 W
  - Pressure: 1.5, 2, 3 mbar
  - Ar:O₂ ratio: 1:3, 1:1, 3:1
- 4 radial positions in the reactor
- 4 tangential positions at the wall
- 5 heights
Gas and Wall Temperatures

- Maximum near the wall
- Increasing with time

![Graph showing gas and wall temperatures](image)

- Red line: electrode center, 5 min discharge
- Orange line: electrode center, 3 min discharge
- Blue line: electrode center, 1 min discharge
- Green line: electrode center, before the discharge

- Parameters:
  - 75 W
  - Ar:O₂ = 1:1
  - 2 mbar
  - 1000 sccm

Radial Position [mm] vs. Gas and Wall Temperature [°C]
Results from the Parameter Study

- Higher plasma forward power
  - Higher heat flux due to the plasma
  - Higher gas temperatures
  - Expansion of the plasma zone

- Higher pressure
  - Contraction of the plasma zone

- Gas composition
  - No main effect in the investigated range
Discharge into the Lower Flange

- Lower flange acts as second grounded electrode
  → Second “Hot Spot” beside the main electrodes

100 W

Change of the setup:
Longer glass tube
1.5 m instead of 0.5 m
Plasma Heating: Spatial Distribution

- No heat flux due to the plasma in the flanges
  - Plasma zone is confined in the glass cylinder!

![Graph showing heat flux distribution](image)

- Heat flux due to the plasma [W/m²]
- Radial position [mm]

- glass tube 1475 mm
- electrode center 1175 mm
- electrode lower edge 1025 mm
- glass tube 725 mm
- glass tube 425 mm
- lower flange 125 mm
Gas Temperature: Spatial Distribution

- Only high gas temperatures in between the electrodes
Effect of Electrode Cooling

- electrodes non-cooled
- glass non-cooled
- glass cooled
- electrodes cooled

Outer Wall Temperature [°C]

Time [s]

100 W
Maximal Particle Temperature Calculation

- Applying the different heat fluxes to a particle
- Typical residence time: 0.068 s
- Electrode cooling, short time operation, no adhesion at the wall:
  - Mean inner wall temperature: 40 °C
  - Mean gas temperature: 45 °C
  - Heat flux due to the plasma: 5000 W/m²

\[ T_{p,max} = 50 \, ^\circ C \]
Particle Temperature

- Dependency on the particle size
Conclusion

- Numerical model
  - particle wall interaction
  - dominant forces
- Parameter study in the original reactor
  - position, power, pressure and gas composition
- Long reactor
  - confinement of the plasma
  - electrode cooling unit
- Particle temperature