12-1 Plasma processes

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flexible processes for network regulation

- with the development of renewable energy we need more flexible industrial plant with dry processes and electrical technic to replace thermal processes and wet technics
- sustainable development need plasma processes which give us high speed for switch on and switch off

A key step :particle /plasma interaction

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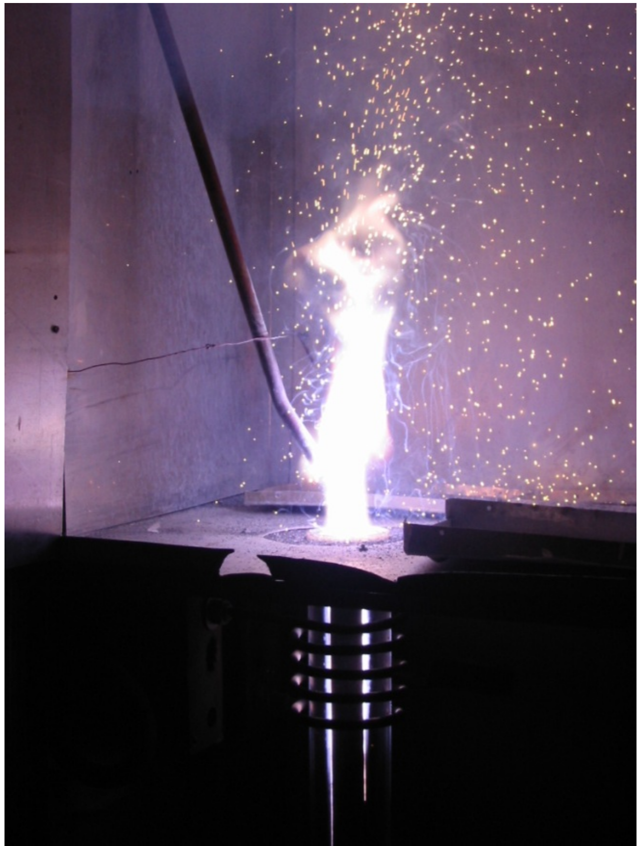
- The main parameters are :
- the residence time
- the energy transfert
- the chemical reactions
- the diffusion phenomena in the
- boundary layer

Inductive coupled plasma for powder treatment

a)



b)

Photos of inductive RF plasma torch of 30 kW
with a contrary current injection of silicon powder:

a – without injection of particles,

b – with injection of particles

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CO_2 dissociation by electron impact

1 – Vitrational state

- $CO_2{}^*({}^1\Sigma^+) \rightarrow CO({}^1\Sigma^+) + O({}^1D)$ E # 7 eV/mol
- $CO_2{}^*({}^1\Sigma^+) \rightarrow CO2^*({}^3B_2) \rightarrow CO({}^1\Sigma^+) + O({}^3P)$ E = 5.5 eV/mol
- $O + CO_2{}^* \rightarrow CO + O_2$ E # 0.5 – 1 eV/mol

2 – Direct electronic impact

- $e + CO_2({}^1\Sigma^+) \rightarrow CO(a^3\Pi) + O({}^3P)$
- $e + CO_2 \rightarrow CO + O^-$

3 – Intermolecular collision

- $CO_2({}^1\Sigma^+) + CO(a^3\Pi) \rightarrow CO({}^1\Sigma^+) + CO\ ({}^1\Sigma^+) + O({}^3P)$

4 – Vibrational excitation of CO

- $CO(X'\Sigma^+,V) + e \rightarrow CO(X^1\Sigma^+,W) + e$

5 – Electronic excitation

- $CO(X^1\Sigma^+,V) + e \rightarrow CO(Y,W) + e$

6 – Ionisation

- $CO(X^1\Sigma^+,V) + e \rightarrow CO+(X^2\Sigma^+,W) + 2\ e$

7 – Dissociation

- $CO(X^1\Sigma^+,V) + e \rightarrow C({}^3P) + O(Y) + e$
- $\rightarrow C(Y) + O({}^3P) + O(Y) + e$

8 – Vibrational relaxation

- $CO(X^1\Sigma^+,V) + CO(X^1\Sigma^+,W) \rightarrow CO(X^1\Sigma^+,V\text{-}1) + CO(X^1\Sigma^+, W + 1)$

9 – Electronic energy emission

- $CO(B'Z^+\ v) \rightarrow CO(A'\Pi,W) + hu$

10 – Recombinaison

- 10.1. $C({}^3P) + O({}^3P)$ + wall $\rightarrow CO(Y,V)$ + paroi
- 10.2. $C({}^3P)$ + wall $\rightarrow$ deposit C_s
- 10.3. $O({}^3P)$ + wall $\rightarrow$ Oads $\rightarrow O_{2g}$ + wall

11 – Dismutation

- $CO(a^3\Pi) + CO \rightarrow CO_2 + C$ wall transfert or catalysis
- $CO(Y,V) + O({}^3P) \rightarrow CO_2{}^*$ + energy on wall

12 – Decomposition

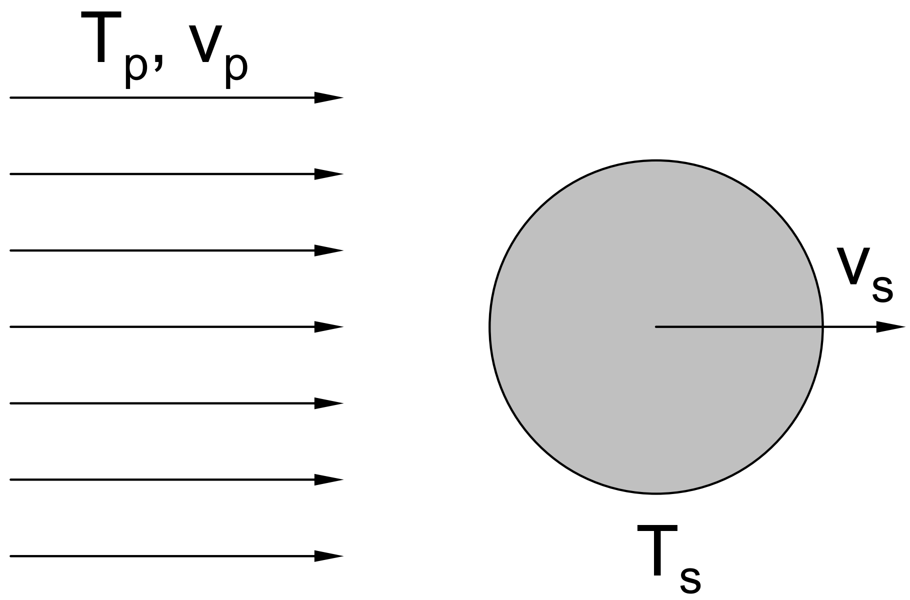
- $CO_2 + C \rightarrow CO + CO$

Model

- Motion of particle in real plasma jet is not considered
- Plasma has constant temperature T_p
- Plasma has constant velocity v_p
- Particle has constant velocity v_s
- Temperature inside the particle is uniform

Equation of balance of energy for particle:

$$m_s c_{ps} \frac{dT_s}{dt} = \sum_i P_i$$



Steps of particle heating

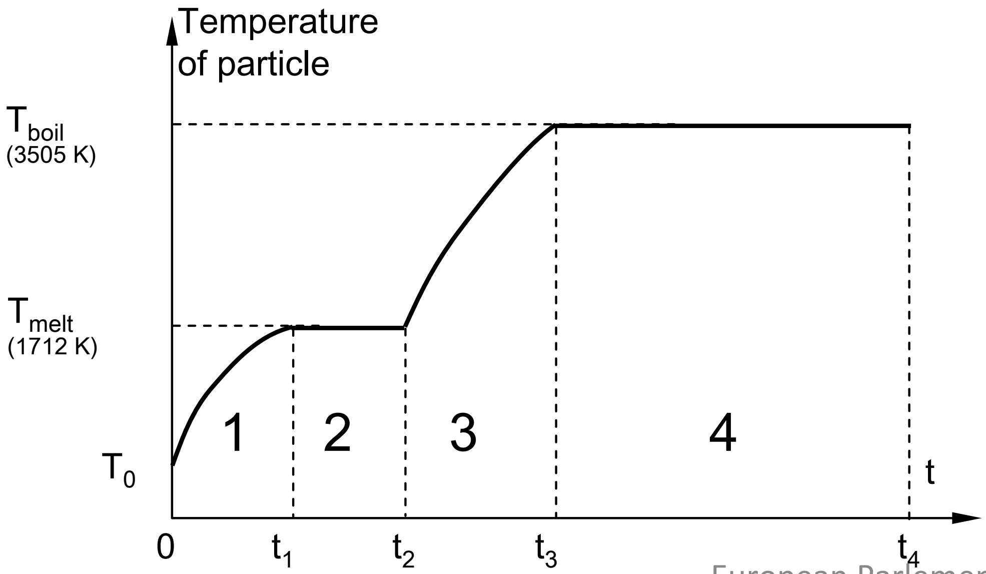
- Heating of solid particle up to melting temperature
- Melting of particle
- Heating of liquid droplet up to boiling temperature
- Boiling of droplet

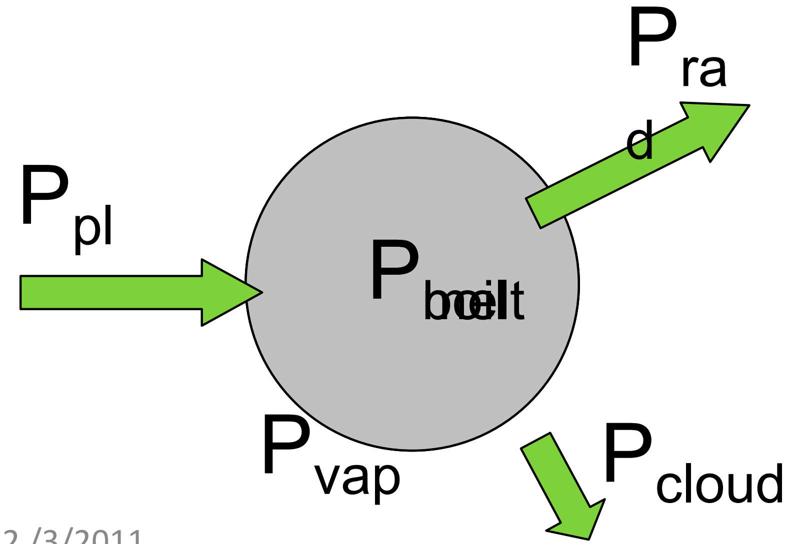
$$m_s c_{p_s} \frac{dT_s}{dt} = P_{pl} - P_{rad}$$

$$m_s c_{p_s} \frac{dT_s}{dt} = 0 = P_{pl} - P_{rad} - P_{melt}$$

$$m_s c_{p_s} \frac{dT_s}{dt} = P_{pl} - P_{rad} - P_{vap} - P_{cloud}$$

$$m_s c_{p_s} \frac{dT_s}{dt} = 0 = P_{pl} - P_{rad} - P_{boil} - P_{cloud}$$





Heat and mass transfer formulas

- Conductive-convective heat transfer from plasma

$$P_{pl} = \left(2 + 0.6 \cdot Re^{0.5} \cdot Pr^{0.33}\right) \cdot \frac{\lambda_p}{d_s} \cdot \left(T_p - T_s\right) \cdot S_{surface}$$

- Radiation of particle

$$P_{rad} = \varepsilon \cdot \sigma \cdot T_s^4 \cdot S_{surface}$$

- Melting of particle

$$P_{melt} = \Delta H_{melt} \cdot \dot{m}_{melt}$$

- Vaporization of particle

$$P_{vap} = \Delta H_{boil} \cdot \dot{m}_{vap}$$

- Boiling of particle

$$P_{boil} = \Delta H_{boil} \cdot \dot{m}_{boil}$$

- Heating of vapor cloud

$$P_{cloud} = \dot{m}_{\substack{vap \\ (boil)}} \cdot \bar{c}_{p\,vapor} \cdot \left(T_p - T_{boil}\right)$$

- Mass losses by boiling

$$\dot{m}_{boil} = \frac{P_{pl} - P_{rad}}{\Delta H_{boil} + \bar{c}_{p\,vapor}\left(T_p\right) \cdot \left(T_p - T_{boil}\right)}$$

- Mass losses by vaporization

$$\dot{m}_{vap} = h_m \cdot S_{surface} \cdot p \ln\left(\frac{p}{p - p_v\left(T_s\right)}\right)$$

Chemical Reaction

- Taking into account of chemical reactions

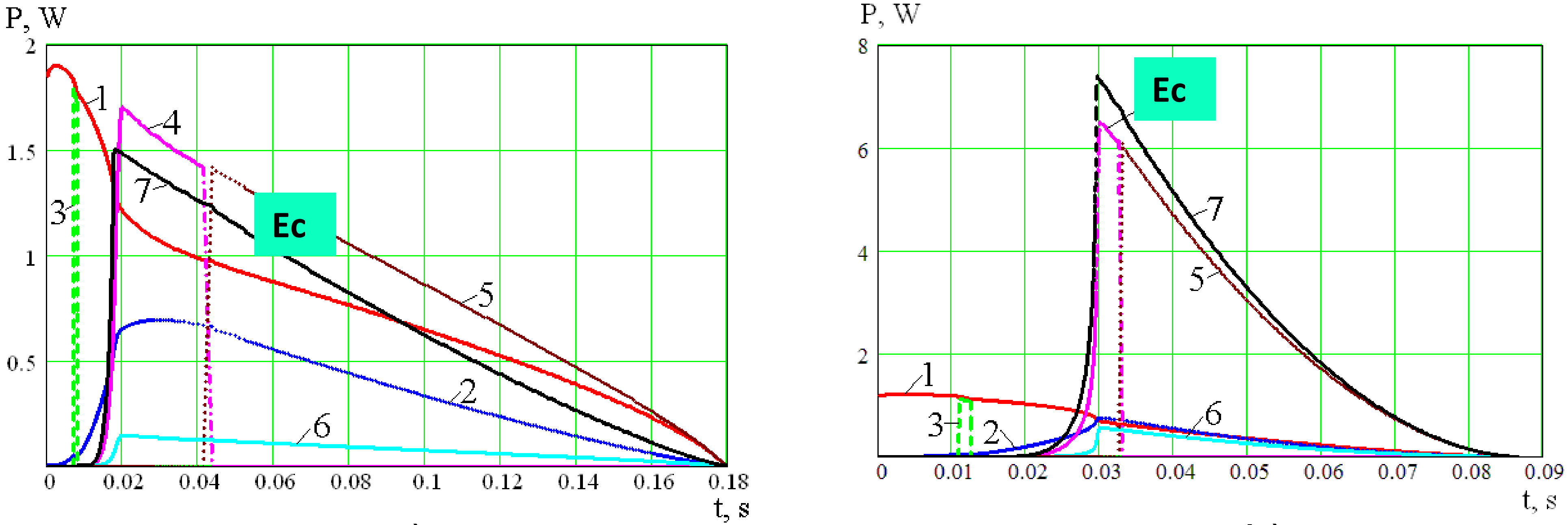
$$m_s c_{ps} \frac{dT_s}{dt} = \sum_i P_i - P_{chem}$$

- Power of chemical reaction

$$P_{chem} = \Delta_r H\left(T\right) \cdot \dot{m}_{react}$$

- Chemical reactions
  - Exothermic reactions $\Delta_r H(T) < 0$
  - Endothermic reactions $\Delta_r H(T) > 0$

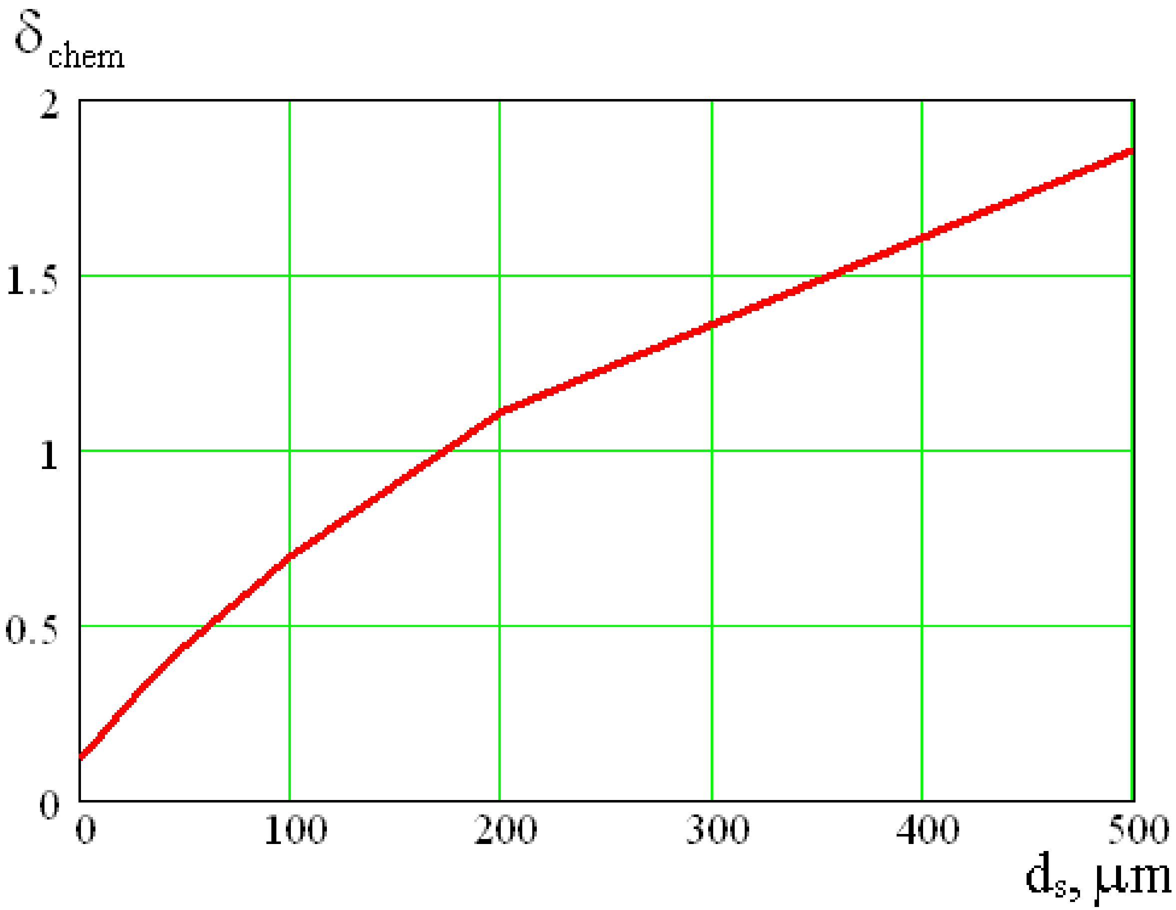
Results: evolution with time of different ways of heat transfer



a) b)

Evolution with heating time of different power sources and losses for particle with velocity relative to plasma respectively of 20 m/s (a) and 100 m/s (b). The particle diameter is 200 μm, the plasma temperature is 5000 K. Different heat transfer : 1 – Ppl, conductive-convective heat transfer from plasma; 2 – Prad, particle losses by radiation; 3 – Pmelt, heat rate of melting; 4 – Pvap, heat rate of vaporization; 5 – Pboil, heat rate of boiling; 6 – Pcloud, vapor cloud heating; 7 – Pchem, power source due to the chemical reaction

Results: dependance on particle diameter



Dependence of parameter δ_{chem} on particle diameter for the case with plasma temperature 5000 K and relative particle velocity 20 m/s

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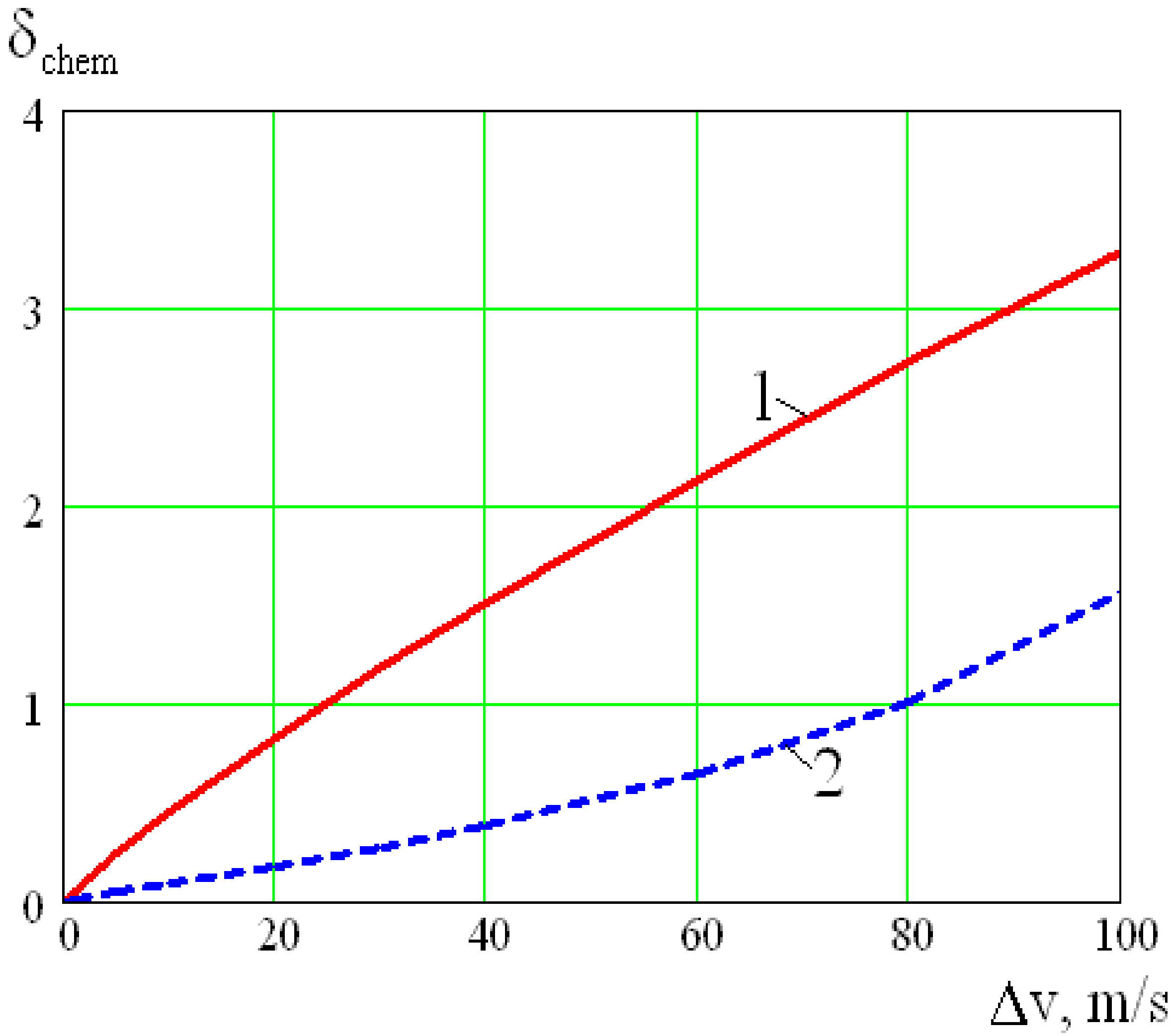
Results: dependence on relative particle velocity



Dependence of parameter δ_{chem} on relative particle velocity Δv for different plasma temperatures :
1 – T_p= 5000 K ; 2 – T_p=7000 K
(particle diameter is 200 μm)