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 transfer
  - the chemical reactions
  - the diffusion phenomena in the boundary layer
Inductive coupled plasma for powder treatment

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
CO₂ dissociation by electron impact

1 – Vibrational state
- CO₂*(1Σ⁺) → CO(1Σ⁺) + O(1D)  E # 7 eV/mol
- CO₂*(1Σ⁺) → CO₂*(3B₂) → CO(1Σ⁺) + O(3P)
  E = 5.5 eV/mol
- O + CO₂* → CO + O₂  E # 0.5 – 1 eV/mol

2 – Direct electronic impact
- e + CO₂(1Σ⁺) → CO(a³Π) + O(3P)
- e + CO₂ → CO + O

3 – Intermolecular collision
- CO₂(1Σ⁺) + CO(a³Π) → CO(1Σ⁺) + CO (1Σ⁺) + O(3P)

4 – Vibrational excitation of CO
- CO(X'Σ⁺,V) + e → CO(X¹Σ⁺,W) + e

5 – Electronic excitation
- CO(X¹Σ⁺,V) + e → CO(Y,W) + e

6 – Ionisation
- CO(X¹Σ⁺,V) + e → CO+(X²Σ⁺,W) + 2 e

7 – Dissociation
- CO(X¹Σ⁺,V) + e → C(3P) + O(Y) + e
- C(Y) + O(3P) + O(Y) + e

8 – Vibrational relaxation
- CO(X¹Σ⁺,V) + CO(X¹Σ⁺,W) → CO(X¹Σ⁺,V-1) + CO(X¹Σ⁺, W + 1)

9 – Electronic energy emission
- CO(B’Z⁺ v) → CO(A’Π,W) + hu

10 – Recombinaison
- 10.1. C(3P) + O(3P) + wall → CO(Y,V) + paroi
- 10.2. C(3P) + wall → deposit C₅
- 10.3. O(3P) + wall → Oads → O₂g + wall

11 – Dismutation
- CO(a³Π) + CO → CO₂ + C  wall transfert or catalysis
- CO(Y,V) + O(3P) → CO₂* + energy on wall

12 – Decomposition
- CO₂ + C → 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

\[
\begin{align*}
  m_s c_p s \frac{dT_s}{dt} &= P_{pl} - P_{rad} \\
  m_s c_p s \frac{dT_s}{dt} &= 0 = P_{pl} - P_{rad} - P_{melt} \\
  m_s c_p s \frac{dT_s}{dt} &= P_{pl} - P_{rad} - P_{vap} - P_{cloud} \\
  m_s c_p s \frac{dT_s}{dt} &= 0 = P_{pl} - P_{rad} - P_{boil} - P_{cloud}
\end{align*}
\]

Pagrams and equations describe the temperature evolution of a particle during these steps.
Heat and mass transfer formulas

- Conductive-convective heat transfer from plasma
  \[ P_p = \left( 2 + 0.6 \cdot Re^{0.5} \cdot Pr^{0.33} \right) \cdot \frac{\lambda_p}{d_s} \cdot (T_p - T_s) \cdot S_{\text{surface}} \]

- Radiation of particle
  \[ P_{\text{rad}} = \varepsilon \cdot \sigma \cdot T_s^4 \cdot S_{\text{surface}} \]

- Melting of particle
  \[ P_{\text{melt}} = \Delta H_{\text{melt}} \cdot \dot{m}_{\text{melt}} \]

- Vaporization of particle
  \[ P_{\text{vap}} = \Delta H_{\text{boil}} \cdot \dot{m}_{\text{vap}} \]

- Boiling of particle
  \[ P_{\text{boil}} = \Delta H_{\text{boil}} \cdot \dot{m}_{\text{boil}} \]

- Heating of vapor cloud
  \[ P_{\text{cloud}} = \dot{m}_{\text{vap}} (\text{boil}) \cdot \bar{c}_{p\text{vapor}} \cdot \left( T_p - T_{\text{boil}} \right) \]

- Mass losses by boiling
  \[ \dot{m}_{\text{boil}} = \frac{P_{\text{pl}} - P_{\text{rad}}}{\Delta H_{\text{boil}} + \bar{c}_{p\text{vapor}} \cdot (T_p) \cdot (T_p - T_{\text{boil}})} \]

- Mass losses by vaporization
  \[ \dot{m}_{\text{vap}} = \dot{m}_{\text{surf}} \cdot \ln \left( \frac{p}{p_p(T_s)} \right) \]
Chemical Reaction

- Taking into account of chemical reactions
  \[ m_s c_{ps} \frac{dT_s}{dt} = \sum P_i - P_{chem} \]

- Power of chemical reaction
  \[ P_{chem} = \Delta_r H(T) \cdot \dot{m}_{react} \]

- 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

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 $\delta_{\text{chem}}$ on particle diameter for the case with plasma temperature 5000 K and relative particle velocity 20 m/s
Results: dependence on relative particle velocity

Dependence of parameter $\delta_{\text{chem}}$ on relative particle velocity $\Delta v$ for different plasma temperatures:

1 – $T_p = 5000$ K; 2 – $T_p = 7000$ K

(particle diameter is 200 $\mu$m)