NUMERICAL ANALYSIS OF Si PARTICLES INJECTION PARAMETERS INFLUENCE ON EVAPORATION PROCESS IN THERMAL PLASMA REACTOR

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ABSTRACT Two phase, 2-D mathematical model was used for numerical analysis of Si (d_{po}<50 μm) particle injection parameters influence on mixing and evaporation process in the axisymmetric reactor. Analysis of the computed results for different values of examined parameters, have shown that critical mechanism for effective particle evaporation is heat transfer, in which heat conduction has primary role while heat transfer by convection and radiation are up to 15% but with opposite contribution. Increase of initial particle diameter, decreases its specific surface area and quantity of heat transferred to the particles (for the same mass flow rate) along the reactor, while particle residence period and reactor length necessary for total evaporation increases. Increase of injection velocity and angle (from $\alpha=0$ - coaxial flow, to $\alpha=\pi/2$ - radial injection) have positive influence on particle penetration into high temperature plasma core and on evaporation process. Analysis have confirmed that for effective evaporation of solid particles in plasma reactor numerous parameters must be considered and carefully optimized.

INTRODUCTION For thermal plasma processing of solid particles, injection and mixing, i.e. momentum, heat and mass transfer between solid particles and plasma flow is of great importance for the quality of the product. This is especially pronounced when Si powder is used as a precursor for plasma Si_3N_4 or SiC powder synthesis. To obtain chemically pure ceramic powder, injected Si particles have to be completely evaporated before gas-phase synthesis reaction take place. There are numerous effects involved in plasma particle interaction having different range of influence in particular plasma process or reactor. Experimental investigation of such a problem is difficult and expensive due to extreme conditions present in two phase high temperature, turbulent plasma flow, so numerical modelling is used for analysis, developing and optimization of the plasma reactor and the process. Paper presents results of numerical analysis of the influence of injection parameters for Si particles (particle initial diameter, injection velocity and angle between annular injection flow and central axial plasma flow, $0<\alpha<\pi/2$) on evaporation process in plasma reactor.

MODEL Analyzed axisymmetric, plasma reactor is schematically shown in Fig. 1. High temperature nitrogen plasma flow enters the vertical chamber of radius R and length L, through the central inlet with radius r_{in} at the top of the reactor. The secondary fluid flow, laden with solid particles at room temperature, is injected from the same side through the conical annular channel with inlet radii r_1 and r_2 and angle α. The products can leave the reactor through a central opening of radius r_{ex} or through an annular exit of radii R_1 and R at the reactor bottom. All reactor surfaces are shielded with uncooled high temperature material and all dimensions (L, R) refer to the inside surfaces of the shield. Computer simulation is based on mathematical model [1] which includes: widely used κ-ε model of turbulence for closing equations of motion for two dimensional plasma swirl flow, Lagrangian Stochastic Deterministic model for calculation of particle motion in plasma flow, PSI-Cell method for computing particle-plasma interaction and six flux method for modelling radiative heat transfer between particles, plasma and reactor wall. Correlations used for interphase

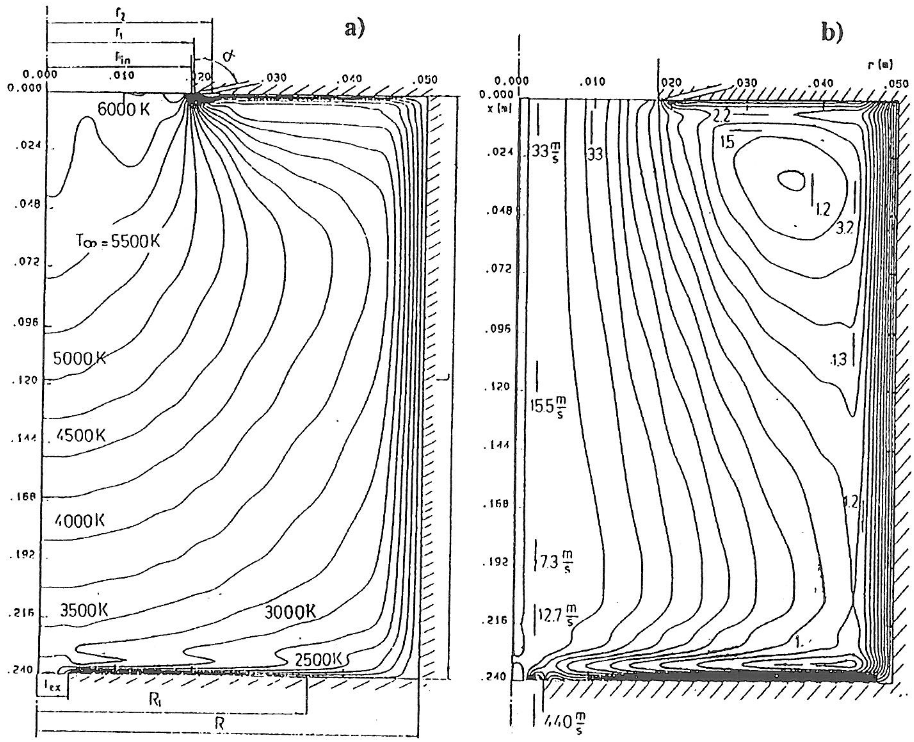

Figure 1. Axial section of the reactor with computed curves of constant: a) plasma temperature and b) stream function for the example with following parameters: $r_1=r_{in}=$ 18.75 mm, $r_2=21.75$ mm, R=50 mm, L=240 mm, $r_{ex}=4$ mm, $T_w=1500$ K, $T_{w,bottom}=1700$ K; nitrogen flow: $m_{in}=2.07$ g/s, $\varphi_{pl}=30°$, $T_{in}=6000$ K, $m_{sec}=0.24$ g/s; silicon powder: $m_{si}=0.127$ g/s, $d_{po}=40$ μm, $\alpha=87.5°$.

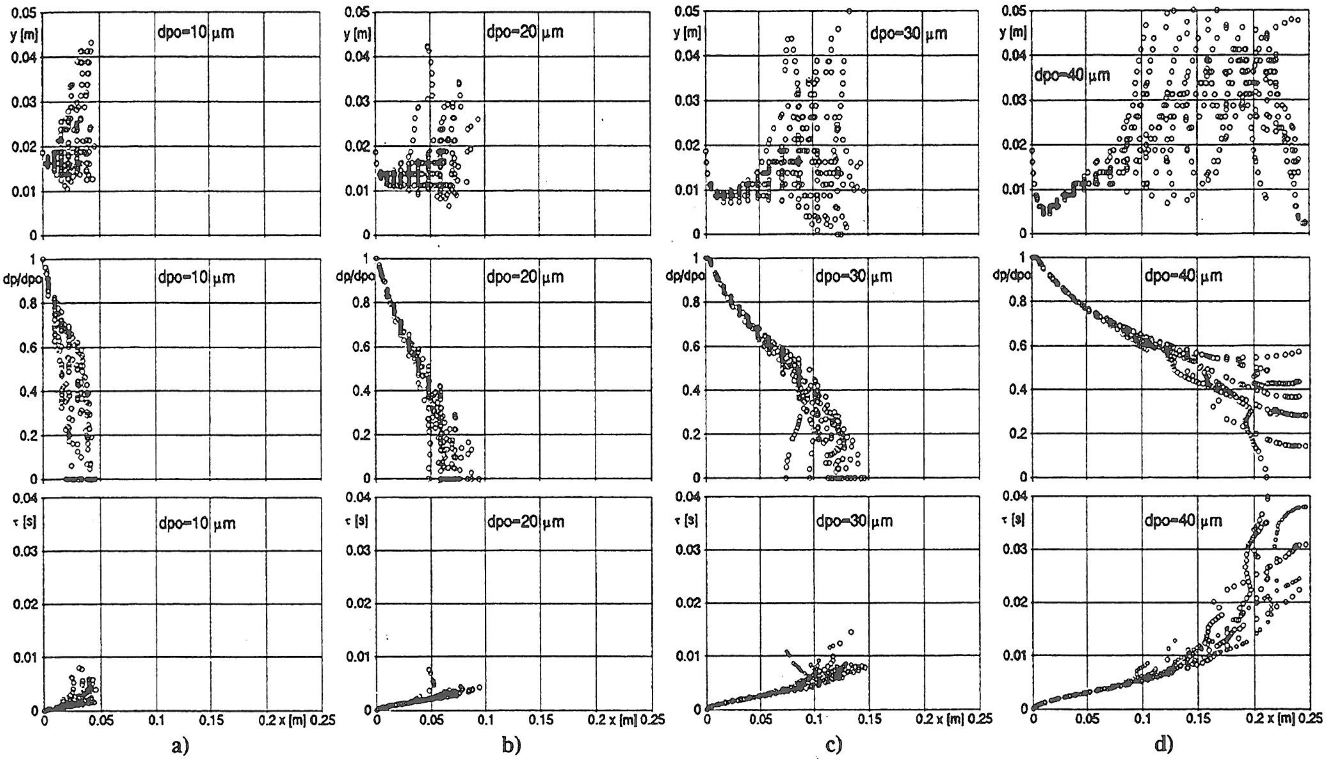

Figure 2 Computed the instantaneous position of some Si particles in axial section of the reactor, relative change of particle diameter d_p/d_{po} along its trace and particle residence period τ, all as a function of particle axial position in the reactor, illustrating influence of particle initial diameter on mixing and evaporation process for the examples: a) $d_{po}=10\mu m$, b) $d_{po}=20\mu m$, c) $d_{po}=30\mu m$, and d) $d_{po}=40\mu m$, with following constant values of common parameters: $r_1=r_{in}=18{,}75mm$, $r_2=21{,}25mm$, $R=50mm$, $L=240mm$, $r_{ex}=6{,}25mm$, $T_w=1500K$; nitrogen plasma flow: $T_{in}=6000K$, $m_{in}=2{,}07g/s$, $\varphi=30°$; Si powder: $m_{Si}=0{,}1268g/s$, $m_{N2}=0{,}24g/s$, $\alpha=87{,}5°$

momentum, heat and mass transfer are based [2] on integral mean values of plasma properties in boundary layer surrounding particles due to high temperature difference in layer, and including Knudsen effects due to small particle diameter.

RESULTS Numerical results obtained by computer simulation will be explained on few examples in which Si particles initial diameter or injection velocity (angle and intensity) were changed, while other common (geometric, fluid mass and temperature) parameters had following constant values: inlet plasma channel radius $r_1 = r_{in} =$ 18.75 mm, outer radius of injection channel r_2 = 21.75 mm, reactor radius R= 50 mm, reactor length L = 240 mm, radius of exit channel r_{ex} = 4 mm, temperature of the shield T_w=1500 K, $T_{w,bottom}$ = 1700 K, nitrogen plasma flow: m_{in} = 2.07 g/s, angle correlating tangential (swirl) W_{in} and axial U_{in} plasma velocity component ($W_{in} = U_{in} tg\varphi_{pl}$) φ_{pl} = 30°, inlet plasma temperature T_{in} = 6000 K, secondary nitrogen mass flow rate m_{sec}= 0.24 g/s, silicon powder mass flow m_{Si}= 0.127 g/s. Axial and radial component of the particle inlet velocity and its starting position in the exit section of the injection channel, where treated as a stochastic parameters, which means that they have random values with Gaussian distribution around mean values defined by mass flow rate of secondary gas and geometric parameters of the channel. For the following analysis and discussion it is essential to have a whole picture of temperature and flow field in the reactor. In Fig. 1 are shown the calculated curves of constant: a) plasma temperature T_∞ and b) stream function in the axial section of the reactor for the case of radial injection (α = 87.5°) of Si particles with uniform initial diameter d_{po} = 40 μm. Practically in the whole reactor there are two different radial zones: central region ($r < r_{in}$) of high axial plasma velocity and high temperature and wide peripheral region ($r_{in} < r < R$) of low plasma velocities ($U < 10$ m/s) and lower temperature with recirculating flow near the top of the cylindrical wall. As a first approximation it can be said that temperature and velocity field in all other presented examples is almost the same or very similar to the one presented in Fig. 1. Influence of Si particles initial size on penetration, mixing and evaporation process is illustrated in Fig. 2. Here are presented calculated instantaneous positions of some particles in axial section of the reactor, relative change of diameter d_p/d_{po}, for the same particles along their trajectory as a function of its axial position in the reactor, and residence period as a function of particles axial position in the reactor, for four different initial Si particles diameters: a) d_{po}=10μm, b) d_{po}=20μm, c) d_{po}=30μm and d) d_{po}=40μm. With the prescribed values of parameters, radial injection of finest Si powder (d_{po}=10 μm) results in poor penetration into central plasma flow ($r \le r_{in}$). The highest concentration of particles is in the boundary layer between central and peripheral zone. Due to high turbulence intensity in boundary layer and quick rise of its thickness, particles with so small mass and momentum are quickly spread into low temperature recirculating flow. In spite of that, due to high specific surface area of the powder, heat transfer is sufficiently high for complete evaporation of all particles at the beginning of the reactor ($x \le 50$ mm) in less than 8 ms. Radial injection of coarser Si powder (d_{po}=20 μm) with the same mass flow rate and unchanged other parameters, results in better penetration and mixing with central high temperature plasma flow, due to higher particle initial momentum. For the same reason, radial dispersion of Si particles in low temperature zone is slower. Higher heat

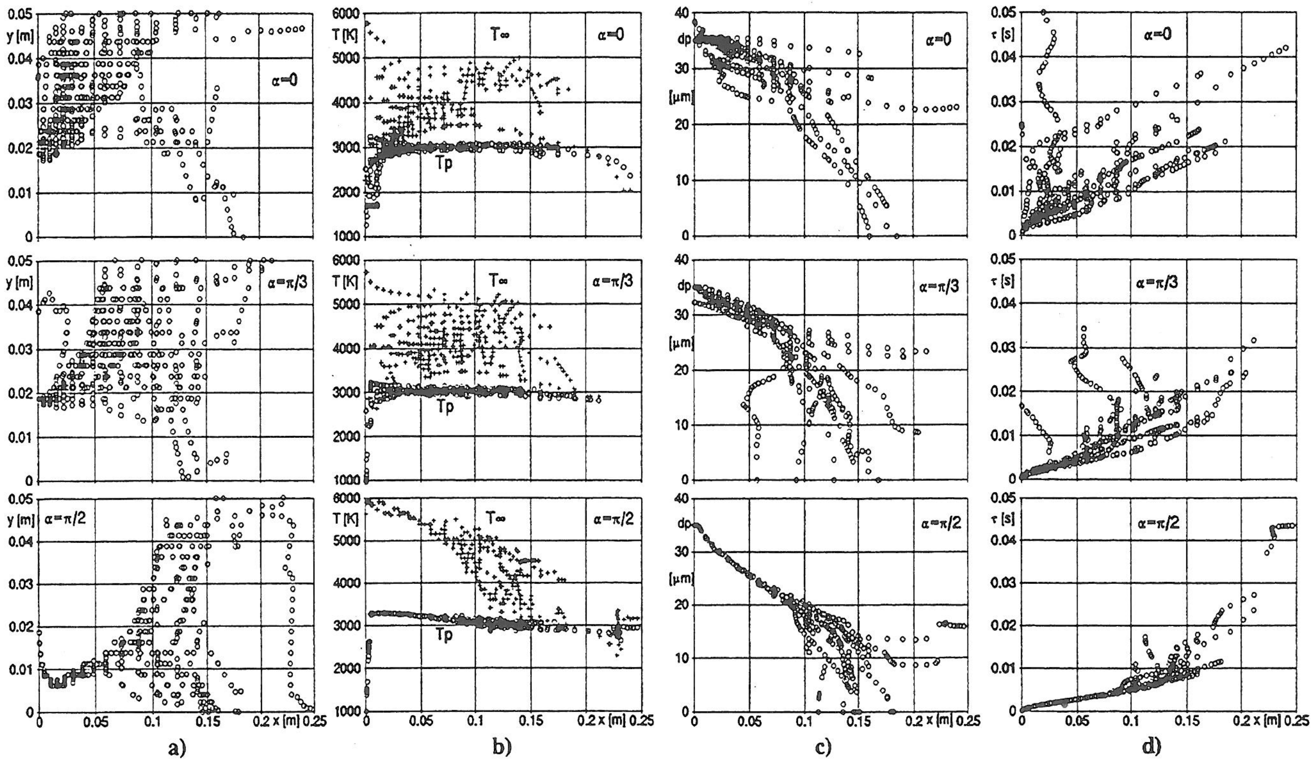

Figure 3. Computed: a) the instantaneous position of some Si particles in axial section of the reactor, b) particles temperature T_p and plasma temperature T_∞, c) change of particle diameter d_p along its trace and d) particle residence period, all as a function of particle axial position in the reactor, illustrating influence of injection angle ($\alpha=0$ top figures, $\alpha=\pi/3$ middle raw figures and $\alpha=\pi/2$ bottom figures) on mixing and evaporation process for the example with following common values of other parameters: $r_1=r_{in}=18{,}75$mm, $r_2=21{,}25$mm, $R=50$mm, $L=240$mm, $r_{ex}=6{,}25$mm, $T_w=1500$K; nitrogen plasma flow: $T_{in}=6000$K, $m_{in}=2{,}07$g/s, $\varphi=30°$; Si powder: $m_{Si}=0{,}1268$g/s, $m_{N2}=0{,}24$g/s, $d_{po}=35\mu$m

transfer rate (compared with previous case, $d_{po}=10\ \mu m$) due to higher plasma temperature along particle trajectory, compensates lower specific surface of coarser Si powder so the residence period up to complete evaporation is the same but axial length of particles trajectories is twice longer ($x \leq 100$ mm) due to higher plasma velocity in central region. With further increase of Si particle initial diameter, mass and momentum (Fig. 2c and d), penetration into high temperature plasma core is improved but dispersion of particles is lower due to higher plasma viscosity, lower turbulent intensity and higher particle mass. Intensive radial spread of Si particles with $d_{po}=30\ \mu m$ starts from $x \geq 50$ mm (Fig. 2c) and for $d_{po}=40\ \mu m$, from $x \geq 75$ mm. Due to high plasma temperature and high heat flux rate along the trajectory, particles of $d_{po}=30\ \mu m$ can be completely evaporated at axial distances $x \leq 150$ mm and residence periods $\tau < 15$ ms. For the Si powder with lowest specific surface area, much longer τ and reactor length are needed for complete evaporation. In the analyzed example (Fig. 1 and 2d, L=240 mm) residence period up to more than 40 ms are obtained (for Si particles with $d_{po}=40\ \mu m$), 96% of the injected Si mass have been evaporated and the rest is deposited on reactor walls or escaped through the reactor exit as droplet.
Influence of conical injection channel angle α on penetration, mixing and evaporation process is illustrated in Fig. 3. Here are presented computed:a) instantaneous positions of some Si particles in axial section of the reactor, b) plasma temperature T_∞ and particle temperature T_p along its trajectory, c) change of particle diameter d_p along its trace and d) residence period, all as a function of particles axial position in the reactor, for three different values: $\alpha=0$, $\pi/3$ and $\pi/2$. Coaxial injection of Si particles ($d_{po}=35\ \mu m$) results in very poor penetration into central plasma flow. Particles are mostly concentrated in periphery recirculating zone (Fig. 3a, $\alpha=0$) where plasma temperature is relatively low and same is heat transfer rate to the particle, its temperature (Fig. 3b) and evaporation rate i.e. particle diameter decrease (Fig. 3c). Recirculating flow enables high residence period but still, more than 50% of injected Si mass have been deposited on reactor walls. For higher angle values ($\alpha=\pi/3$, middle row diagrams) better penetration and mixing in the boundary layer of central plasma flow could be obtained. Plasma temperature in this region is higher increasing heat transfer rate and particle temperature (Fig. 3b, $\alpha=\pi/3$), while decreasing residence period (Fig. 3d). In case of radial Si powder injection ($\alpha=\pi/2$, bottom row diagrams), highest penetration into high temperature plasma core, highest heat flux rate and particle temperature level is obtained resulting in highest evaporation rate and complete evaporation of Si particles in shortest period. In the case $\alpha=\pi/3$, less than 30% of injected Si mass is deposited on reactor walls while for $\alpha=\pi/2$ it is less than 1%.
In the case of radial Si powder injection, increase of injection velocity helps particle penetration into high temperature plasma core and increases evaporation rate, but it must be carefully optimized.

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