The application of RF inductively coupled plasma torch for the enrichment of natural quartz

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Abstract. Numerical simulations of the dynamics of the heating of polydisperse quartz flow in the plasma and the thermal stresses arising in quartz particles are performed. As a plasma source, an RF inductively coupled plasma torch with axial supplies of plasma and sheath gases is considered. The RF inductively coupled plasma torch with 3-turns works at a generator frequency of 3 MHz and an electrical power up to 10 kW. Polydisperse quartz flows (carrier gas and quartz particles) are introduced into the plasma after discharge zone through the azimuthally symmetrical annular channel at an angle of 60° to the axis of the plasma torch. Pure argon and its mixtures with hydrogen (with a volume fraction of up to 5%) are considered as working gas.

1. Introduction

One of the most promising technologies for the production of high purity quartz (HPQ) concentrate at a finishing stage is the plasma method [1]. By this method the concentration of total impurities in the pre-enriched quartz concentrate (grains with standard sizes 0.1 – 0.4 mm) could be reduced to values less than 20 ppm. The principle of this method is based on the treatment of fine quartz particles in a high temperature (~ 5 – 10 kK) plasma jet generated by a plasma torch. The quartz particles are unsteady heated to temperatures below their melting point (their residence times in the plasma jet $t_p \sim 10^{-3} - 10^{-2}$ s). As a result of thermobaric destruction and plasma chemical desorption, evaporation of low-melting impurities from the split surfaces of particles, the mineral impurities (including part of structural impurities from the lattice) and gas-liquid inclusions could be effectively removed. The experimental results [1, 2] proved that the enrichment of various types of quartz concentrates for obtaining HPQ at the final stage could be realized in the plasma torch with electric power up to 20 kW. However, during the process of quartz concentrate in electric arc torch [2], the vapors and microparticles of various metals (arc materials) are always present in the plasma flow and pollute the enriched concentrate.

To minimize the contamination of HPQ concentrate, it is necessary to use the electrodeless RF inductively coupled plasma (RF-ICP) torches. However, until now the information on the enrichment efficiency of quartz particles in plasma flows of RF-ICP torches is practically absent. Therefore, a wide range of computational research is substantially needed to evaluate the prospects of using RF-ICP torches in the enrichment technology.

In this work, a series of numerical calculations of the dynamic of heating of polydisperse quartz flow in the plasma and the thermal stresses arising in particles are performed. The working conditions of RF-ICP torch system for the thermal destruction of polydisperse quartz particles are determined.
2. Physical and mathematical model.

The configuration and main parameters of the RF-ICP torch system are shown in figure 1 and table 1, respectively. The plasma $Q_2$ and sheath $Q_3$ gases are axially introduced into the RF-ICP torch. Pure argon and its mixtures with hydrogen are considered as the working gases. The volume fraction of hydrogen $\alpha$ varies from 0 to 5%. The quartz particles (with sizes of 0.1 – 0.4 mm) are introduced into plasma-reactor by the carrier gas $Q_1$ through an annular channel at an injection angle $\theta = 60^\circ$ (with $r$-coordinate) with speed $U_p = U_1 * K_p$. Where the modulus of carrier gas velocity at the exit of annular channel is $U_1 = 15$ m/s, the coefficient of correction for the velocity of particles $K_p$ depends on their diameters $d_p$. The dynamic of heating of particles takes place during the mixing of cold polydisperse quartz flow with plasma.

The mathematical model for heating quartz particles and the thermal stresses arising in them includes two stages. At the first stage, the dynamics heating of a polydisperse two-phase flow is calculated [3]. In this case, the temperature in the particles is assumed uniformly. At the second stage, the obtained results about the dependences of particle temperature on the time are used as boundary conditions (particle surface temperature) for solving the unsteady heating of particles and calculating the thermal stress field [4].

![Figure 1](image-url) **Figure 1.** Configuration of RF-ICP torch system for enriching quartz particles: 1 – annular carrier gas channel with quartz particles, 2 – plasma gas channel, 3 – peripheral slotted sheath gas channel.

| $R$ | $R$ | $R$ | $R$ | $\delta_1 = 2.2$ mm | $\delta_2 = 3.5$ mm |
|-----|-----|-----|-----|---------------------|---------------------|
| $\delta_3 = 1.5$ mm | $\delta_4 = 4$ mm | $Z$ | $Z$ | $Z$ |
| $Z$ | $d$ | $\alpha = 0 - 10\%$ |
| $P$ | $\omega = 3$ MHz | $\theta = 60^\circ$ | $d_p = 0.1 - 0.4$ mm | $s$ |

In the study of gas dynamics and the process of heating particles in the system of RF-ICP torch, the spiral inductor is assumed as three parallel cylindrically symmetric turns. The discharge current is uniformly distributed over the cross section of the inductor coil. The flows of the plasma and sheath gases, as well as the polydisperse flow of carrier gas with quartz particles at the inlets are azimuthally symmetrical and stationary. Under the fulfillments of these assumptions, the electromagnetic and gas-dynamic equations can be written under the 2D $(r, z)$ model in cylindrical coordinates $(r, \theta, z)$ [5]. In order to predict the mixing process of polydisperse quartz flows with plasma, the standard $k$-$\varepsilon$ turbulent model is used [6].

At the first stage, the study of polydisperse quartz flows in the plasma are carried out within the framework of a two-phase collisional model [7, 8], taking into account the effect of particles on the gas.
The system of equations included Maxwell’s equations; gas dynamic equations, taking into account the electromagnetic forces, Joule heat, radiation loss and effects of particles; equations of particles motion and heat exchange with plasma gas [8]:

\[
\nabla \cdot (\rho U) = 0, \\
\n\nabla \cdot (\rho U U) = -\nabla p + \nabla \cdot \tau + \rho \frac{d\varepsilon}{dt} + \frac{1}{2} \text{Re} \left\{ \mathbf{J} \times \mathbf{B}^2 \right\} - \mathbf{F}_{\text{rad}}, \\
\n\n\nabla \cdot \left( \rho \mathbf{h} \cdot U \right) = \nabla p + \nabla \cdot \left( \frac{\mu_{\text{eff}}}{C_p} \nabla T \right) + \frac{1}{2} \text{Re} \left\{ \mathbf{J} \times \nabla E^2 \right\} - Q_{\text{rad}} - \alpha A_p (T - T_p),
\]

Where \( \mu_{\text{eff}} \) and \( \lambda_{\text{eff}} \) are the effective viscosity and thermal conductivity of gas mixture, respectively [6]. \( \mathbf{E} \), \( \mathbf{B} \) and \( \mathbf{J} \) are the electric and magnetic fields, as well as the induction current in plasma, which are determined by solving the system of Maxwell's equations. \( Q_{\text{rad}} \) is the volumetric radiation loss. \( \mathbf{F}_{\text{rad}} = \left( \rho C_d / 8 \right) \mathbf{U} \cdot \nabla \mathbf{U} \left( \mathbf{U} - \mathbf{U}_p \right), \) \( A_p = n S_p \) is the interfacial area between particles and gas per unit volume, \( S_p = \pi d_p^2 \) is the surface area of a single particle [3].

Under an approximation of uniform temperature distribution in the particles, their motion and heating process in the plasma could be described as follows [8]:

\[
\frac{d(m_p U_p)}{dt} = \left( \rho C_d / 8 \right) S_p \left( \mathbf{U} \cdot \nabla \mathbf{U} \left( \mathbf{U} - \mathbf{U}_p \right) + m_p \frac{d\varepsilon}{dt} \right), \tag{4}
\]

\[
m_p \frac{d(C_p T_p)}{dt} = \pi d_p^2 \left[ \alpha_p \left( T - T_p \right) - \varepsilon_p \sigma_p T_p^4 \right], \tag{5}
\]

At the second stage, the analysis of the spatial-temporal distributions of thermal stress in a quartz particle under unsteady heating is made by solving the Fourier – Kirchhoff equations and the equilibrium equation written by the displacement vector \( \mathbf{u} \) [4].

\[
\rho_p(T_p) C_p(T_p) \frac{\partial T_p}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left( \lambda_p(T_p) \cdot r^2 \frac{\partial T_p}{\partial r} \right), \tag{6}
\]

\[
\frac{\partial}{\partial r} \left( \frac{1}{r^2} \frac{\partial u}{\partial r} \right) = \frac{1 + \sigma}{3(1 - \sigma)} \alpha_p(T_p) \left( \frac{\partial T_p}{\partial r} \right) \frac{\partial T_p}{\partial r}, \tag{7}
\]

Where the temperature on the particles surface \( T_h(r=d_p/2) \) is obtained from the numerical solution of equations (1 – 5) and will be considered as one of the boundary conditions for equation (6). \( \alpha_p(T_p) \) is the coefficient of volume expansion, depending on the particles temperature.

The boundary conditions for the system of equations (1 – 7) are set in accordance with [4, 9]. The thermophysical parameters of plasma and quartz particles are obtained from the theoretical and experimental data [10, 11]. The mechanical properties of quartz particles (tensile \( \sigma_t \) and compressive \( \sigma_c \) strengths, Poisson's ratio \( \sigma \) and modulus of elasticity \( E \) ) are given in [12]: \( \sigma_t \geq 50 \) MPa, \( \sigma_c = 1.1 \) GPa, \( \sigma = 0.12, E = 90.5 \) GPa. The equivalent thermal stress \( \sigma_{eq} \) for assessing the split conditions of particles (\( \sigma_{eq} \geq \sigma_t \) ) is determined according to Mohr–Coulomb theory. The numerical solutions of the systems of equations (1 – 5) and equations (6 – 7) are carried out in ANSYS by the finite volume method and the finite element method, respectively.

3. Results and Discussion

The spatial distributions of the gas-dynamic parameters of a two-phase flow, as well as the dynamics of motion and heating of quartz particles are calculated and discussed. The analysis of numerical results shows that in pure argon plasma under relative small mass flow rate (\( G_{502} \leq 1 \cdot 10^4 \) kg/s), the small
quartz particles with a diameter of 0.1 – 0.2 mm are overheated above their melting point \((T_m \approx 1900 – 1950 \text{ K})\). In those cases the large particles with a diameter of 0.3 – 0.4 mm could be heated up to 600 K, the maximum equivalent thermal stress in the particles center \(\sigma_{\text{equ}}^{\text{max}}\) is found below their tensile strength \(\sigma_t\). Therefore, there will be no any thermal destruction of these large particles. With increasing the mass flow rate to \(G_{\text{SiO}_2} \geq 1 \cdot 10^3 \text{ kg/s}\), the maximum temperature of small particles \(d_p = 0.1 \text{ mm}\) is below their melting point (figure 2). However, in the center of large particles \((0.3 – 0.4 \text{ mm})\) the maximum equivalent thermal stress \(\sigma_{\text{equ}}^{\text{max}}\) decreases with an increase of the particles mass flow rate.

![Figure 2](image_url)

**Figure 2.** Changes of temperature on particles surface \(T_p\) (solid lines) and equivalent thermal stress in particles center \(\sigma_{\text{equ}}\) (dashed lines) with time under \(G_{\text{SiO}_2} = 1 \cdot 10^3 \text{ kg/s}\): 1 – pure argon, \(d_p = 0.1 \text{ mm}\); 2 – \(\alpha = 5\%\), \(d_p = 0.1 \text{ mm}\); 3 – pure argon, \(d_p = 0.4 \text{ mm}\); 4 – \(\alpha = 5\%\), \(d_p = 0.4 \text{ mm}\).

In order to realize the unsteady heating of particles with larger temperature gradients and ensure their thermal destruction, it is necessary to intensify the process of heat exchange from the plasma gas to particles. As a result, the argon-hydrogen mixture instead of pure argon gas is used as working gases.

It can be seen that with an increase of the volume fraction of hydrogen \(\alpha\) from 0 to 5\%, the maximum temperature on the particles surface increases in 1.5 – 2 times (figure 2). In those cases small particles with a diameter less than 0.2 – 0.25 mm will be overheated. For large particles \(d_p = 0.3 – 0.4 \text{ mm}\), the maximum equivalent thermal stress their center is in 1.5 – 2 times higher than the tensile strength: \(\sigma_{\text{equ}}^{\text{max}} \approx 2 \cdot \sigma_t = 90 – 100 \text{ MPa}\). Therefore, the addition of hydrogen into argon plasma can lead to a thermal destruction of all the particles with diameter 0.1 – 0.4 mm.

Due to the loading effect (a decrease in the temperature of a two-phase flow), the maximum particle temperature decreases with increasing the mass flow rate of particles [7]. The minimum mass flow rate \(G_{\text{SiO}_2}^{\text{min}}\), at which the maximum surface temperature of particles \((d_p = 0.1 \text{ mm})\) is less than the melting point of quartz, depends on the volume fraction of hydrogen \(\alpha\) (figure 3). When \(\alpha = 5\%\) the minimum mass flow rate of particles \(G_{\text{SiO}_2}^{\text{min}} \approx 4 \cdot 10^4 \text{ kg/s}\).

The particles temperature and the equivalent thermal stress monotonically decrease with increasing their mass flow rates. At certain value of mass flow rate the maximum equivalent thermal stress \(\sigma_{\text{equ}}^{\text{max}}\) in large particles \(d_p = 0.4 \text{ mm}\) decreases to their tensile strength \(\sigma_t\). It was found that the maximum mass
flow rate of the quartz flow $G_{\text{SiO}_2}^{\text{max}}$ also depends on the volume fraction of hydrogen $\alpha$ (figure 3). When $\alpha = 5\%$ the maximum flow rate $G_{\text{SiO}_2}^{\text{max}} \approx 1\cdot10^{-2}$ kg/s. Note that in the region with relative small hydrogen volume fraction $\alpha \leq 3\%$, the $G_{\text{SiO}_2}^{\text{max}}$ and $G_{\text{SiO}_2}^{\text{min}}$ practically coincide with each other.

Figure 3. Dependences of the maximum mass flow rate $G_{\text{SiO}_2}^{\text{max}}$ and minimum specific energy cost $\eta_{\text{min}}$ (solid lines), minimum mass flow rate $G_{\text{SiO}_2}^{\text{min}}$ and maximum specific energy cost $\eta_{\text{max}}$ (dashed lines) on the volume fraction of hydrogen $\alpha$: 1 – mass flow rates $G_{\text{SiO}_2}$; 2 – specific energy costs $\eta$.

One of the most important power-engineering parameters for evaluating the treatment efficiency of quartz particles in plasma flow is the specific energy cost: $\eta = P/G_{\text{SiO}_2}$. For the maximum $G_{\text{SiO}_2}^{\text{max}}$ and minimum $G_{\text{SiO}_2}^{\text{min}}$ mass flow rates of quartz particles, their corresponding values of specific energy cost $\eta_{\text{min}}$ and $\eta_{\text{max}}$ also depend on hydrogen volume fraction. Figure 3 shows that $\eta_{\text{max}}$ and $\eta_{\text{min}}$ monotonically decrease with the increase of hydrogen volume fraction. When $\alpha = 5\%$ the values of $\eta_{\text{max}}$ and $\eta_{\text{min}}$ are about 0.22 and 0.35 MJ/kg.

4. Conclusions

The numerical results show that the use of RF-ICP torch of pure argon plasma is not applicable for the enrichment of polydisperse quartz particles $d_p = 0.1 – 0.4$ mm. Under those working conditions when small particles with $d_p = 0.1 – 0.2$ mm aren’t overheated (above the melting point), the maximum thermal stress arising in large particles (larger than 0.3 mm) is less than the tensile strength and they couldn’t be split. As a result of the intensification of heat exchange processes between plasma and quartz particles, the use of argon-hydrogen mixture as the working gas makes it possible to provide a more non-uniform heating condition of particles and higher thermal stress in them for splitting. The dependences of the minimum and maximum mass flow rates of the quartz particles, and their corresponding specific energy costs on the volume fraction of hydrogen are established. With an increase of the volume fraction of hydrogen from 0 to 5\%, the maximum mass flow rate of quartz particles and the minimum specific energy cost in RF-ICP torch system rise up. Under $\alpha = 5\%$ the allowable mass flow rates of quartz
particles and their specific energy costs varied in the range of $4 \times 10^{-3} – 1 \times 10^{-2}$ kg/s and 0.22 – 0.36 MJ/kg, respectively.

5. References
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