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Impact of heat transfer on spheroidization of titanium alloys

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Abstract

The industrial application of the spheroidization process using high-temperature plasma is regarded as a good method for the conversion of irregularly shaped particles into a spherical shape. High temperature and controlled plasma conditions are required to obtain satisfactory results. Given this, a 3D model was used to simulate heat transfer from a source term to titanium-alloy particles using ANSYS Fluent software. Such models consider the effects of particle treatment on thermodynamic and transport properties of the plasma. This present study aims to investigate the impact of heat transfer on the particles and the effect of radiation energy loss on the particles, using numerical analysis. The results showed that the operating condition such mass flow was inversely proportional to the rate of heat transfer between plasma particles and the characteristics of the plasma gas, which was due to significant variation in radiation energy losses.

Keywords: Spheroidization, heat transfer, and radiation energy loss

NOMENCLATURES

d_P	[m]	Particle diamete
ρ_P	[kg/m^3]	Particle density
μ	[kg/m.s]	Molecular viscosity of the fluid
R_e	[Dimensionless]	Reynold number
m_p	[kg]	Particle mass

G_k= generation of turbulence kinetic energy due to the mean velocity gradients.
Y_M=contribution of the fluctuating dilatation for compressible turbulence to the overall dissipation rate.
$C_{1\varepsilon}, C_{2\varepsilon}$= constants
σ_k, σ_ε = are the turbulent Prandtl numbers k and ε.
S_k and S_ε= user-defined source terms
$\vec{r}$= position vector
$\vec{s}$= direction vector
$\vec{s}'$= scattering direction vector
a= path length
s= absorption coefficient
n= refractive index
σ_s= scattering coefficient
σ= Stefan-Boltzmann constant (5.67x10^{-8} W/m^2 K^4)
I= radiation intensity, which depends on the position $\vec{r}$ and direction $\vec{s}$.
T= local temperature
Φ = phase function
Ω'= solid angle
Ti = titanium particle
Q_{net}= net energy to apply on a particle
Q_{cv} = energy transfer due to conduction and convection
Q_r = energy transfer due to radiation
h = heat transfer coefficient
A_p = area of the particle

1. Introduction

Numerical models of heat treatment of solids in high-temperature flows, generated in inductive plasma torches, have been developed by many researchers for the past decades. Various mathematical models were developed to study the inter-phase momentum, energy transfer, and plasma-particle interactions that accompany the treatment of powders. These practices had been challenging due to the complexity of the process. When particles pass through the plasma, they can melt and evaporate and these phenomena are critical aspects in most studies (Miao L. *et al.*, 2020). Prof. Pierre Fauchais (Fauchais, 2018) investigated heat transfer to the particles in the plasma torch. He had described three effective energy transfer devices, and the most simple is the inductively coupled torch (ICT). The ICT is an electrodeless device where the energy required for the ionization of electrons (Yoon; *et al.*, 1996), carrier gas, and additional reactive gas (hydrogen, helium or nitrogen, etc.) injection parameters impact greatly the process. These treatments present turbulence in the process and most models of plasma spheroidization describes how the heat is transferred between plasma and particles in a different form. Some authors used computational fluid dynamics (CFD) to study such phenomena. In consideration of heat transfer mechanisms, there is a critical aspect to note. It is the effect of radiation exchange on particle temperature. Some authors had tended to neglect it, but it would be more accurate to count every energy loss no matter the amount. For radiation to be considered, Du and his collaborators

(Du *et al.*, 2018) summarized the three important aspects of radiation namely, (1) size of particles; (2) high surface temperature and high emissivity; (3) low enthalpy difference between the surface of a particle and the plasma. Authors such as Chen and his colleagues in (Chen *et al.*, 1982) considered radiation effect on particle heating or melting in the case of a low-temperature difference between plasma and particle. The small particles tend to emit energy to their surroundings and the plasma to the surface of the particles. These parameters can automatically change the pattern of the entire process. Some heat losses from plasma occur due to the load of the particles. A laboratory study was performed by Prof. V. Colombo (Colombo V. *et al.*, 2013) found that the feed rate was not proportional to the evaporation of solids. It was observed that in the case of a high flow rate, there is partial evaporation. High particle loading cools the plasma and to outcome this challenge, an increase in the power is necessary, resulting in a high cost of production (Jianyi G. *et al.*, 2010). An important aspect to consider in the spheroidization process is the interaction between plasma and particles, the energy transferred affects the temperature history of the process, for example, the heat loss from the particles due to the increase in the feed rate. Another study was done by Prof. Watanabe (Watanabe *et al.*, 1996) in which they used numerical analysis on titanium carbide to investigate the relationship between heat transferred from plasma and the powder, it was observed that this heat transfer was also affected by the loading rate of particles and this resulted in non-efficient melting of the powders. The feed rate inside the plasma flow must be kept at optimum conditions to prevent an excess of heat or fast cooling of particles. In the case of low plasma temperature, particles with large sizes have higher radiation energy loss and Prof. Boulos (Boulos *et al.*, 2017) demonstrated that in such a situation more energy is needed to increase the plasma temperature to compensate for such losses. The industrial application of the radiation process has become more useful since it can be analyzed through computational fluid dynamics (CFD) simulations. From five different radiation models available, the P1 radiation model was chosen in this study because it demands less CPU time to solve all possible equations (ANSYS, 2013).

This paper attempts to investigate the impact of heat transfer on the particles, the effect of radiation energy loss on the particles, through an injection of titanium particles in a continuous flow of argon plasma gas.

2. Numerical method

To get clarification on the heat treatment of titanium in plasma spheroidization, a 3D model with a source term was used to simulate this process. Governing equations for conservation of mass, momentum, and energy are also considered and are described below (see Equations 1-3). Because this model involves plasma-particles interaction, and it presents turbulent flow inside the reactor, the standard k-ε model was adopted to help in defining the flow and temperature fields during the trajectories of particles inside the plasma torch (El-Hage *et al.*, 1998). The model includes equations of kinetic turbulent energy (see Equation 4) and dissipation rate (see Equation 5) that are provided by FLUENT (ANSYS, 2013).

Mass conservation

$$\nabla \, . \, \rho u = S_p^c \tag{1}$$

Momentum conservation

$$\rho u \, . \, \nabla u = -\nabla p + \nabla \, . \, \mu \nabla u + \mathrm{J \times B} + S_p^M \tag{2}$$

Energy conservation

$$\rho u - \nabla h = \nabla . \frac{k}{C_P} \nabla h + \sigma E^2 - Q_r + S_p^E \tag{3}$$

where source term S^E_p represents energy release in a plasma ball and energy exchange due to particles presence,

Turbulence kinetic energy

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{4}$$

Turbulence dissipation rate

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + G_{3\varepsilon}G_b) - C_{2\varepsilon}\frac{\varepsilon^2}{k} + S_\varepsilon \tag{5}$$

Some aspects involved in heating a small particle: Heat received from plasma by conduction, convection, and radiation which is heat loss from the surface of the particle to its surrounding. This is presented in Equation (6) and the heat transfer coefficient is estimated using Equation (7) where the Nussel number is a function of Reynolds and Prank number coefficients, respectively.

$$Q_{net} = Q_{cv} - Q_{sr} = hA_P(T_\infty - T_s) - A_P \varepsilon \sigma_s (T_s^4 - T_a^4) \tag{6}$$

$$Nu = \frac{hd_p}{k} \tag{7}$$

$$Nu = 2.0 + 0.6\, Re^{0.5} Pr^{0.3} \tag{8}$$

To solve radiation using the P1 model, two things are to be considered, absorption and scattering coefficients at position $\vec{r}$ in the direction $\vec{s}$ (ANSYS, 2013). indicated in Equation (9):

$$\frac{dI(\vec{r},\vec{s})}{ds} + (a + \sigma_s) I(\vec{r},\vec{s}) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I(\vec{r},\vec{s}') \Phi(\vec{s}.\vec{s}') d\Omega' \tag{9}$$

Table 1: Boundary conditions summary

Parameter	Value
Probe inlet	r =1.7 mm
Central inlet	r =15.1 mm
Sheath gas inlet	r =4 mm
Outlet	r =55 mm
Plasma torch length	L_R=200 mm
Plasma torch radius	r =25 mm
Reactor chamber length	L_C=910 mm
Source term volume	V= 7.26x10^{-5} m^3
Carrier gas	Q_1=2 l/min
Central gas	Q_2=10 l/min
Sheath gas	Q_3=40 l/min
Particle feed rate	$\dot{m}_P$=10 g/min
Mean diameter	$\bar{d}_P$=50,70 90 µm

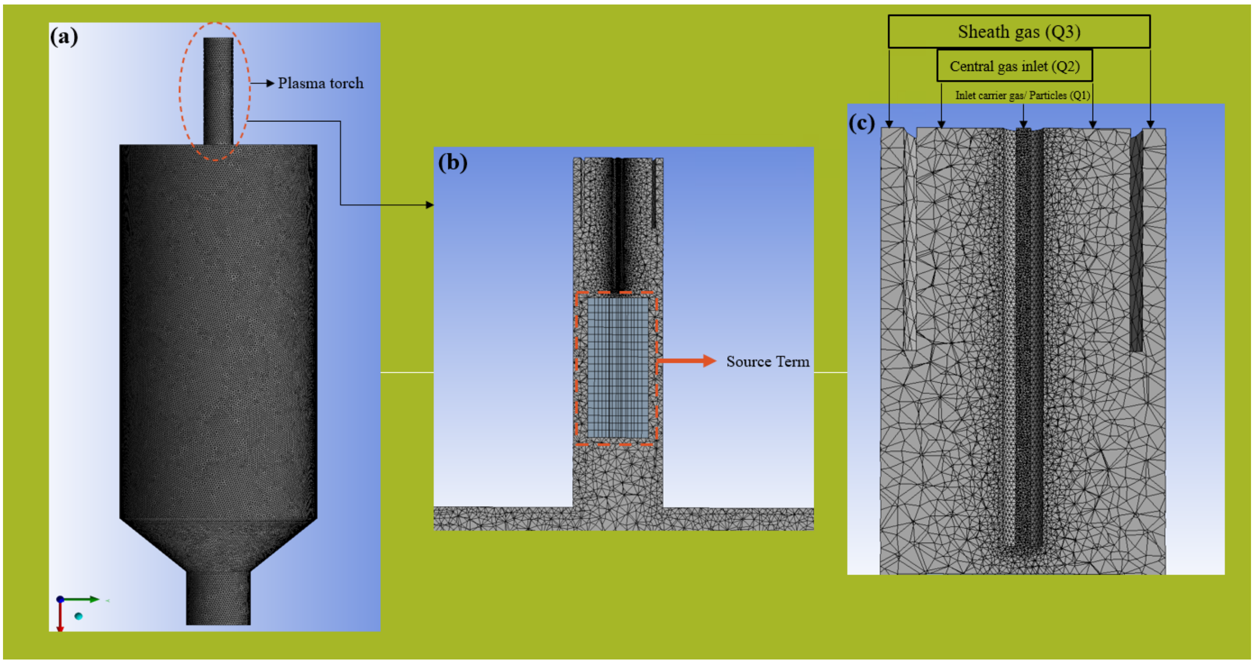

Figure 1: Schematic design of a 3D model using ANSYS Fluent to simulate titanium particles in the argon plasma flow.

3. Simulation procedure

Simulation procedures of titanium particles in continuous flow with argon have consisted of the plasma torch and the chamber with the following assumptions: K-ε turbulence model, radiation is used using P1 model, argon gas is pure gas, particles were spherical, particle size distribution was characterized using the Rosin-Rammler function and the particles are injected into the torch at the same velocity with the carrier gas. The details of dimension and boundary conditions are summarized in Table 1.

4. Results and discussion

Titanium particle movement in plasma flow was simulated through Euler-Lagrange approaches. The results are presented as follow, due to the low enthalpy of argon gas, the effect of radiation on the particles with a range of 50-90 µm respectively was calculated by using the approximated radiation data of argon gas using the approximation of Plank mean absorption coefficient (Bartlova *et al.*, 2014). From the simulation results, the net energy was calculated for the very same purpose.

The results show a dramatic change (see Figure 2) in the heat transfer between plasma particles due to the radiation effect, solid lines represent the particle temperature with radiation, and the dashed lines no radiation involves. It is observed that the radiation enhances the temperature of the particles because the particles are not emitting much energy to its surrounding and this presented a dramatic temperature drop in the plasma gas compared to the results show (see Figure 3) in the absence of radiation effect. The results in the three data sets show that as the size of particles increases there is high energy loss and necessitates more power input in the source term, this is compared to results with no radiation effect whereby Ti particles are only being heated up. Titanium particles with small size are likely to receive enough energy to efficiently reach their molten state and radiation loss is tended to be less for large particles because there is a slight difference in temperature field for Ti with a diameter of 90 µm (see Figure 3) and the increase in radiation loss has caused the volumetric emitted radiation energy to be approximately 15% average of the input total power in the source term. The plasma flow is cooled during the movement of Ti particles along their trajectories, which is caused by the increase

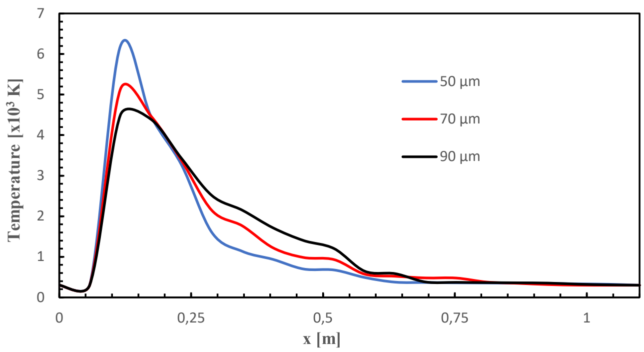

Figure 2: Axial temperature profile along the centerline with the influence of radiation on particles with the size of 50, 70, and 90 µm respectively, and 15 kW power input.

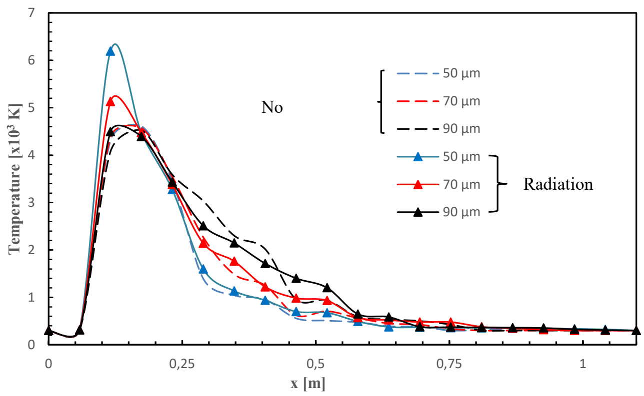

Figure 3: Particle temperatures in the presence and absence of radiation. Solid lines represent the particle temperature with radiation, and the dashed lines no radiation involves.

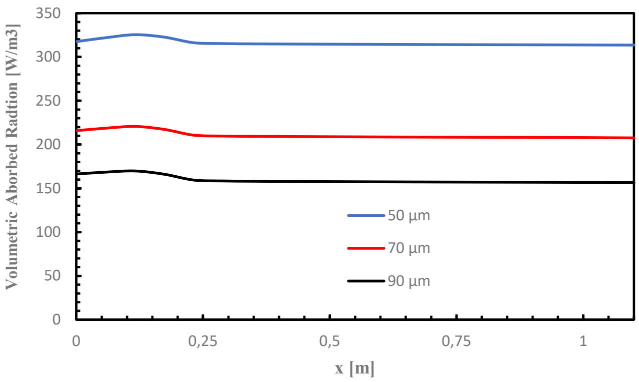

Figure 4: Effect of titanium particle size on the volumetric absorbed radiation

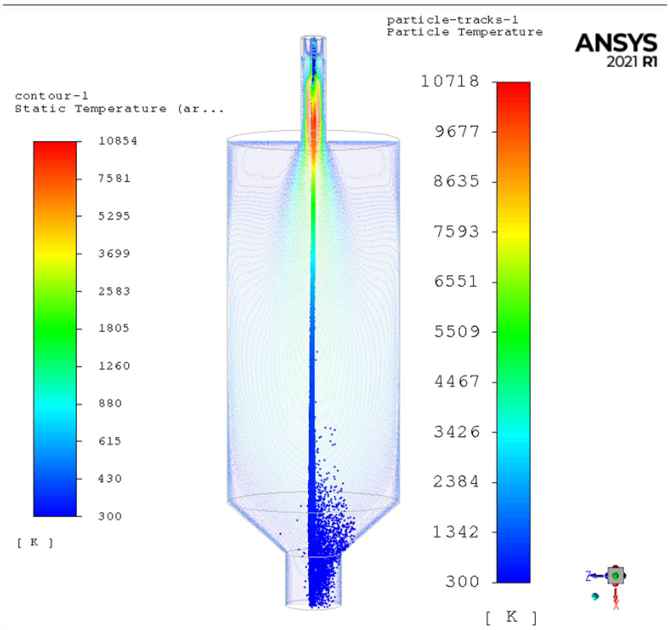

Figure 5: Representation of temperature contour plot of plasma gas and particles tracks temperature for titanium particle with the size of 90 µm.

of radiative energy losses and drop in the heat exchange between plasma and injected solids (see Figure 5). This can be stated that radiative energy loss is found to be the main cause of the decline in energy exchange in the treatment of particles.

Table 2: Effect of heat transfer summary

Size (µm)	Q_{cv}(W)	Q_r (W)	Q_{net} (W)
50	6.77x10^{-2}	11.5x10^{-2}	1.08x10^{-2}
70	1.39x10^{-2}	10.6x10^{-2}	9.18x10^{-2}
90	2.12x10^{-2}	10.3x10^{-2}	8.17x10^{-2}

Table 2 demonstrates that the net energy is quickly decreasing due to the surface temperature of Ti particles, and heat loss due to radiation is found to be higher than the heat transfer due to conduction and convection increase because of the increase in the size of particles. Considering for example titanium particles with a diameter of 50 µm, they can completely melt in plasma gas, in contrast with the case when the particle diameter increase, as observed (see in Figure 2). The volumetric absorbed radiation decreases along with the size increase. For particles with the size of 90 µm diameter have absorbed radiation equal to 154 W/m^3 (see Figure 4) and to simulate particles with an initial size above 90 µm, with the same input source term, there would be difficulties in the emission of radiation to the surroundings and this requires more net energy to overcome this challenge and for such diameter, the plasma temperature should be above 10 000 K.

5. Conclusion

The findings reveal the importance of radiation impact in plasma spheroidization between the gas and particles, to study the performance of radiation in the source term. The simulation demonstrated that the presence of radiation in the simulations has enhanced the temperature of the system. During the interaction of gas radiation and Ti particles, the exchange in temperature distribution was observed. The particles with small size were found likely to have more effective heat transfer because of the high surface temperature of the particle.

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