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Original Research Paper

Discovering the feasibility of using the radiation forces for recovering rare earth elements from coal power plant by-products

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ABSTRACT

The feasibility of using laser separation for rare earth recovery from coal ashes was explored. To do so, laser-induced motion and travel distances of some rare earth and rare earth oxides (Lu_2O_3, Yb_2O_3, HfO_2, Dy_2O_3, Ta_2O_5, Tm, Lu, Ho, TeO_2, La_2O_3, Ho, TiO_2, Fe_2O_3 Y_2O_3, GeO_2, Sc_2O_3) and mineral compounds (MgO, CaO, Al_2O_3, SiO_2, KCl) that are commonly found is coal ashes were numerically investigated. The investigations were carried out for particles in quiescent air, ($T = 300$ K, $\mu = 18.46 \times 10^{-6}$ N s/m^2, $\rho = 1.177$ kg/m^3) exposing to a CW laser beam of 6 mm in diameter and it was focused by a 500 mm focal length lens. The results showed that the separation distances between these elements varied from few micrometers to several millimeters and it became widened as the laser power increased. The important result presented here is that all rare earth oxides were separated and concentrated in a small area located near the beam waist while all other mineral compounds traveled further and concentrated in a small area far from the beam waist.

1. Introduction

Recently, it has been reported that the concentrations of many rare earth elements in coal ashes could be enriched up to within the range of mineral ore deposits, suggesting that coal ashes are the potential resources for rare earth recovery [1,2]. Several extraction methods have been used [2]. Generally, these procedures include initial acid leaching of ash materials, followed by material removal, separation, and purification. These separation steps are chemically intense and generate significant amount of waste streams because they require the use of large amount of water, leaching acids, caustic precipitates and organic solvents [3–6]. Each of these chemical components must be strictly handled to avoid unintended environmental release. The waste streams must be treated because coal ash residuals contain many trace elements that are hazardous elements with As, Cd, Hg, Pb, Se, and many others. For these reasons, there is a need for a safer, more environmental friendlier approach for rare earth recovery [7–17].

Since a photon carries both energy and momentum, when it interacts with a particle, photon–particle energy and momentum transfer occurs resulting in mechanical forces acting on the particle. If the particle is absorptive, the energy transfer is significant, the particle is heated and a temperature gradient exists on its surface. In this case, the force is categorized as the photophoretic force due to the surrounding gas molecules that rebound off the particle surface at different velocities. If the particle is non-absorptive or hardly absorbs the photon, the momentum transfer during refraction and reflection of the photon becomes dominant. In this case, the resulting force is called the photon pressure force. The pressure force composes of two forces: the gradient force acts transversely and the scattering (axial) force acts in the direction along with the photon propagation. Thus, when a laser beam is irradiated onto a coal ash cloud, the various elements of the coal ash will experience these radiation forces. They will be pulled into the higher intensity region of the beam in the transverse plane by the gradient force and simultaneously pushed along with the beam propagation direction by the scattering force. Since the magnitudes and directions of the radiation forces depend mainly on the particle properties such size, shape, thermal properties, and refractive index, these elements will move and displace at different speeds, directions, and distances, leading to spatial separations. This suggests that, by utilizing the radiation forces, the various components contained in a coal ash can be spatially separated and recovered without the need of using extraction solvents and leaching acids.

Use of a laser beam to manipulate and separate micron/nano-size particles has been reported [18–25]. In these studies, separation of transparent particles such as glass, silica, PMMA, polystyrene, nickel and aluminum oxides particles in water using a loosely focused Gaussian beam were investigated. The effects of

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various parameters including, numerical aperture, focal length, laser power, particle size, refractive index, and medium velocity on the parting distance, the number particles separated per unit time were studied. This study will explore the feasibility of using the radiation forces for sorting and separating the various rare earth compounds contained in coal fly and bottom ashes. It is noted that laser separation of particles is achieved based on the motion and displacement, known as the retention distance of each particle induced by the thermal/momentum exchange between particles and photons carried by the laser beam. To explore such feasibility we, therefore, will conduct a series of numerical calculations given to the laser-induced motion of some typical rare earth compounds that are commonly found to present in coal ashes. The goal is to evaluate and observe the differences in their trajectories, their retention distances as they move down stream and finally escape from the laser beam. The calculations will be carried using quiescent air as a medium. Separation of rare earth compounds from coal ash in air is more preferable in terms of environmental impact. Other advantages are due the low viscosity and refractive index of air. A low refractive index leads to a greater radiation force. Thus, particles in air will move faster and farther resulting in a larger separation distance and higher separation throughput. In addition, since these compounds may include both absorptive and non-absorptive species, the photon force equations developed by the previous investigators might not be useful. We, therefore, will develop a system of equations that accounts for the result of the particle extinction coefficient for this proposed application.

2. Theoretical consideration

When a particle is dropped into a loosely focused laser beam, since the curvature of the wave is negligible [18,26], photon streams are assumed to travel in the direction parallel to the laser propagation direction and interact with the particle via reflection, refraction, absorption, and transmission as represented in Fig. 1. The forces acting on the particle are: the gravity force, the photophoretic force, the photon pressure force, and the viscous force. The gravity force, F_g induces the particle downwards motion. The photophoretic force F_{phtr}, which is due to the particle heating, controls the axial motion of the particle. The photon pressure force, which is induced by the direct transfer of the photon momentum to the particle during refraction and reflection, composes of two components: the scattering component F_x controlling the particle axial motion and the gradient component, F_y controlling the particle motion in the direction perpendicular to the axial direction. The viscous force, which is resulted due to the particle motion, resists the particle motion. Therefore, the particle motion in x and y-directions can be described as

$$\rho_p \frac{4\pi a^3}{3}\frac{d\upsilon_x}{dt} = F_x + F_{phtr} - F_{d,x} \tag{1}$$

$$\rho_p \frac{4\pi a^3}{3}\frac{d\upsilon_y}{dx} = F_y - F_{d,y} - F_g \tag{2}$$

The x-component velocity, υ_x and the y-component velocity, υ_y are

$$\frac{dx}{dt} = \upsilon_x \tag{3}$$

$$\frac{dy}{dt} = \upsilon_y \tag{4}$$

In these equations, $F_g = 4\pi a^3 \rho_p g/3$ is the gravity force, ρ_p is the particle density, a is the particle radius, g is the gravitational accelerator. The drag forces $F_{d,x}$ and $F_{d,y}$ acting on the particle in x and y-directions, respectively, are

$$F_{d,x} = 6\pi a \mu \upsilon_x \tag{5}$$

$$F_{d,y} = 6\pi a \mu \upsilon_y \tag{6}$$

where μ is the viscosity of the medium. It has been known that, in the limit where the Knudsen numbers $Kn = l/a$, (where l is the mean free path of the molecules of the surrounding gas and a is the particle size) are considerably less than 1 a surface temperature gradi-

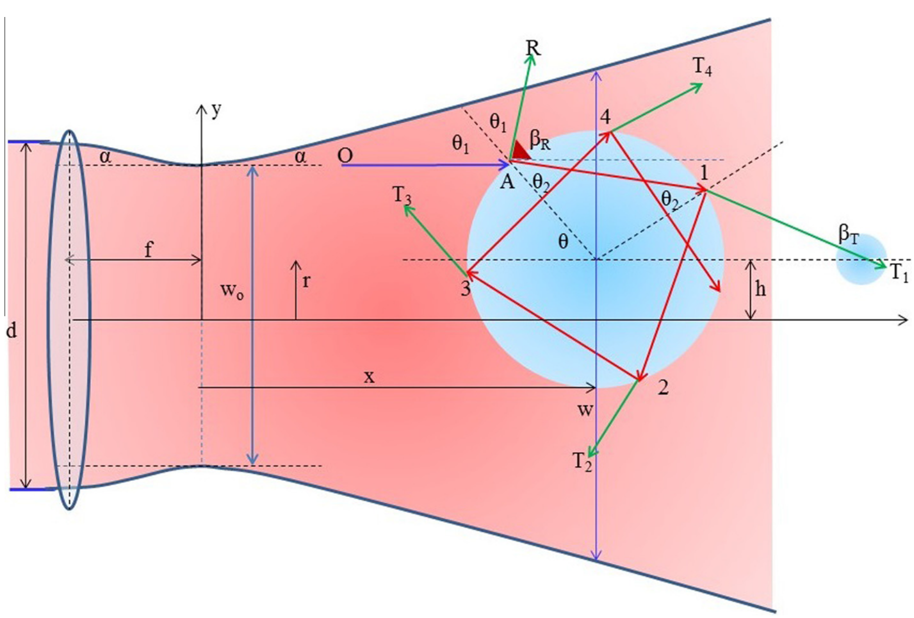

Fig. 1. Geometrical representation of a Gaussian beam and its interaction with a particle showing the photon ray OA, its reflection AR and refraction at A1 and multiple internal reflection beams: 12, 23, 34, etc. and multiple transmission beams $1T_1$, $2T_2$, $3T_3$, $4T_4$, etc., (d is the beam diameter, f is the focal length, w_o is the beam waist, w is the beam width, r is the beam radius h is the distance from the particle to the beam center, x is the location of the particle in the x-direction, y is the vertical direction α is the beam divergent angle, β_R is the reflection angle of AR, β_T is the angle makes by the transmission beam with x-direction, and θ, θ_1, and θ_2 are angles as indicated in the figure).