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Deoiling of oil-coated catalyst using high-speed suspending self-rotation in cyclone

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ABSTRACT

Disposal of waste catalysts has posed considerable threat to the environment and biological health. It has been confirmed that the self-rotation of particles in a hydrocyclone can enhance the efficiency of removing pollutants in catalyst particles. This paper presented the high-speed suspending self-rotation of catalyst particles in cyclone with the help of microfluidic technology and high-speed camera test. The oil-removal efficiency can be improved further by controlling the self-rotation speed and suspending time. Results showed that under the inlet flux of 35 m^3/h, catalyst particles had a self-rotation speed of more than 14,000 rad/s in cyclone, 80 times as that of the revolution speed under the same operating condition. The self-rotation speed and suspending time of catalyst particles can be enhanced by the increase of inlet flux and cone angle. The coating oil is removed under the periodic resultant centrifugal force when the suspending time is prolonged, and the oil content can be reduced from 36.17% to less than 4% within 100 s in cyclone under 25 °C. This finding is highly significant to non-thermal purification of waste catalyst under gas–solid environment.

1. Introduction

Petroleum porous waste catalyst is a major pollutant to the environment. The mass emission of oil-containing waste catalyst not only destroys the ecological structure of soil [1] but also leads to continuous migration and infiltration of contaminants within the water cycle, thereby posing a long-term hidden threat on the health of living creatures and human beings because polymer residual substance, such as aromatics, is difficult to degrade naturally [2]. The United States Environmental Protection Agency (EPA) and the Ministry of Environmental Protection of China listed waste catalyst that contains hydrocarbon produced during the refining of petroleum as hazardous and T-grade waste in 2000 [3–5], respectively. The purification and recovery of waste catalyst has always been the focus of attention around the world. At present, methods including incineration、landfill、extraction separation and high-temperature pyrolysis are mainly adopted to treat oily waste catalysts [6,7]. In the early 20th century, EPA [8] used hot water to deoil contaminated soil. Feng [9] later used high-pressure water column with strong shear flow to clean oily soil. Li [10] achieved a removal effeciency of spent hydrotreating catalysts close to 90% while producing a large amount of oily waste wate. Zhou [11] applied the adsorption method to the pyrolysis of oily sludge to improve the pyrolysis efficiency. However, problems, such as secondary pollution, incomplete clear up, and huge energy consumption, are occurring in these methods [12,13]. According to the data analysis of Nature [14], the annual energy consumption of chemical separation is up to 50% of the total in the United States. At present, many researchers are aiming to reduce the separation energy consumption as well as improve the separation efficiency by controlling the motion behavior of particles under turbulence condition [15], which greatly increases the treatment intensity during the process [16,17].

Klein et al. [18] used the inertial particles of 7 cm to monitor the rotation and migration behavior of particles in Kármán turbulent flow and found that the rotation speed of particle in the turbulent flow is far greater than that of migration. Marcus et al. [19] investigated the rotation dynamics and Lagrange vorticity measurement of particles by using marked 3D-printing particles and proved that the rotation speed of particles in the swirling flow field is far larger than that of other particles in the same turbulent flow field condition. Bhaskar et al. [20] applied CFD to simulate particle motion in the swirling flow field. Narasimha et al. [21] predicted the trajectory of the spiral motion of particles in the swirling flow field. Many researchers have applied this trajectory to analyze the rotation behavior of particles in flow fields because of the development of camera technology [22–24]. Meyer et al. [25] has

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Nomenclature

r	radius of microsphere revolving (mm)
r_s	diameter of microsphere (mm)
D_1	spillway diameter of hydrocyclone (mm)
D_2	cylindrical diameter of hydrocyclone (mm)
D_3	hydrocyclone underflow diameter (mm)
L	length of the entrance (mm)
S_1	length of the upper overflow section (mm)
S_2	length of the lower overflow section (mm)
S_3	length of column section (mm)
S_4	length of cone section (mm)
l_1-l_5	displacement of microsphere
Q	inlet flux (m^3/h)
ΔP	pressure drop between inlet and overflow of cyclone
U	inlet velocity (m/s)
U_Z	revolution speed (m/s)
C	critical capacity of catalyst particle (mg/cm^3)
Re_D	characteristic Reynolds number
v_m	feeding rate (kg/s)
F	centrifugal force of the particle (N)
f	friction between particles and wall (N)
F_N	wall pressure of particle (N)
F_D	air drag force of particle (N)
F_Z	centrifugal force generated by particle revolution (N)
F_{zr}	radial component of F_z (N)
F_P	centrifugal force generated by particle rotation (N)
F_{pr}	radial component of F_p (N)
F_{rr}	coupling centrifugal force (N)
F_r	centrifugal separation factor
w	The energy consumption of the deoiling process (kJ/kg)

Greek letters

α	cone angle of hydrocyclone (°)
θ	Azimuth angle of spherical coordinates (°)
φ	elevation angle of spherical coordinates (°)
ψ	angle of microsphere transition (°)
μ	dynamic viscosity of fluid (Pa s)
ρ	density of particle (kg/m^3)
ω_p	self-rotation speed (rad/s)
ω_Z	revolution speed (rad/s)

discovered that the self-rotation of spheres is controlled by the large scales of turbulence through measurement of spherical and ellipsoidal particles rotation in homogeneous, isotropic turbulence. A spin motion of particles would occur when the velocity between two ends of the particle is different [26]. As there is a large velocity gradient in the cyclone, especially in the boundary layer near the wall [21], the fluid velocity at both ends of the particle is unequal while the force at both ends of the particle is uneven, causing the self-rotation of particle. The self-rotation speed of a particle in cyclone is equal to half of the shear strain rate at that point. [19,27]. Yang [28] has utilized the strong turbulence in mini-hydrocyclone to efficiently treat the MTO industrial wastewater with fine particles. Huang [29] has teated the self-rotation speed of the microspheres which is more than 1000 rad/s when Reynolds number is no more than 7×10^3 in the hydrocyclone and applied this to catalyst deoiling. Particle has been proven to have greater rotation speed and separation potential in swirling flow field with a strong shear flow. Huang et al. [29] proposed that the high-speed self-rotation of droplets in hydrocyclone should result in higher mass transfer force on both sides of the interface, thus enhancing mass transfer efficiency; however, further research on residence time should be conducted. Lim et al. [30] used cyclone to separate aerosols and realized the purpose of altering the behavior of particles by structural adjustment. This paper proposed to study particle motion in the swirling turbulent flow field and complete the regulation of particle rotation speed and time to be applied to the purification and recovery of waste catalyst.

Experiments show that when the structure of the cyclone and the properties of particles change to a certain extent (i.e., Stairmand HE), particles are no longer rapidly discharged along the spiral line, instead, they hover around the cone region of the cyclone, which is a recirculation motion of suspended state. The recirculation motion of suspended state directly increases the processing cycle of particles, thereby increasing the residence time of particles in the cyclone remarkably. Moreover, of the constant update of the interface with other phases can be developed, thus, the deep purification can be achieved. This phenomenon is important in enhancing the separation efficiency of equipment and guiding specific operations.

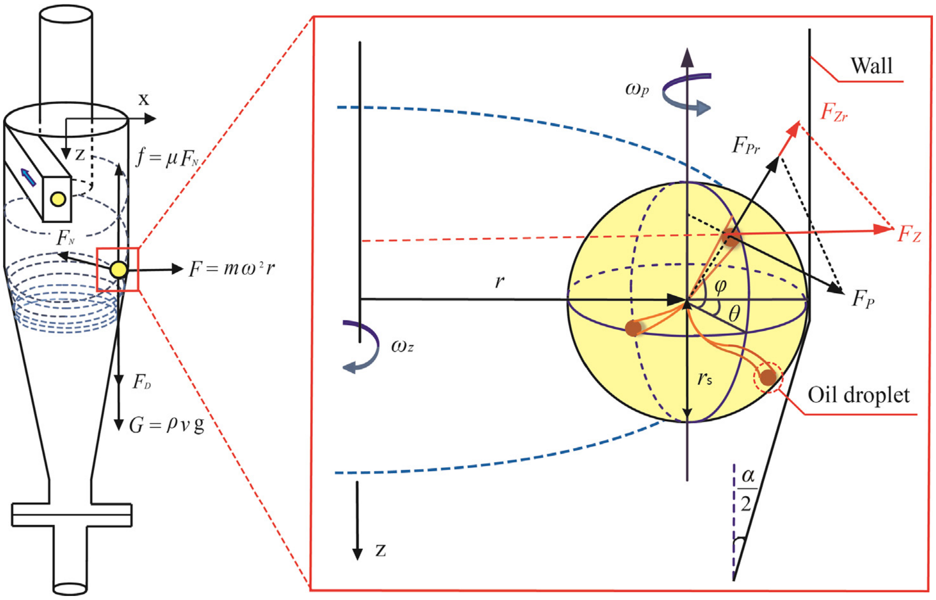

Fig. 1. Analysis of coupling force on catalyst particles.