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Impact of particle agglomeration in cyclones

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ABSTRACT

The purpose of this work is to build a model to predict in a more realistic way the collection efficiency of gas cyclones, and in particular, of numerically optimized cyclones, that show very high collection efficiencies for sub-micrometer particles. These cyclones can be coupled to recirculation systems for further improving the collection efficiencies of these fine particles.

As a first approach, in this paper a reverse-flow gas-cyclone without recirculation was studied. The model starts by solving the particle trajectory in a predetermined flow field inside the cyclone on which turbulence is superimposed by adding random fluctuating components. By employing a fixed set of parameters, it determines if a collision or an agglomeration occurs. In case of agglomeration, the initial particles will have a dynamic behavior inside the cyclone as an newly formed agglomerate, thus having a different collection efficiency from that of the original particles. In fact, the observed efficiency will increase above theoretical predictions for un-agglomerated particles and this can be observed in various experimental results.

The hypothesis of particle agglomeration within the cyclone turbulent flow seems a sound justification for the higher than predicted collection efficiencies observed for smaller particles in a gas-cyclone, being expectable with recirculation that this effect will become even more significant.

1. Introduction

Collection efficiency models currently developed for gas cyclones, such as the Mothes and Löffer's model [1], can predict with good accuracy the collection efficiency of particles with diameters above about 2–3 μm.

Experimentally, several authors have observed at laboratory, pilot and industrial-scales [2–10] that cyclone systems can have much higher collection for fine particles (below about 3 μm) than predicted by classical models, viz. grade-efficiency curves may show a minimum in collection at an intermediate particle size (ranging from about 0.8 to 2 μm). Since these hook-like curves do not always occur [2,7], the phenomenon, whatever its cause, is probably dependent on the physical properties of the powders, on the gas flow field inside the cyclone or on both.

Muschelknautz's model [7,11–13] predicts, at high solid loadings, a fairly constant value of collection efficiency for the smaller particles, since it is postulated that a portion of the feed is separated unclassified, but it does not predict the abnormal high collection for fine particles observed for dilute systems at low or moderate loadings (feed concentrations 1–10 g_{powder}/m^3_{gas}).

This work proposes that this abnormal behavior for fine particles is attributed to agglomeration within the cyclone turbulent flow field, as initially postulated by Mothes and Löffler [14], much as it happens in recirculating fluidized beds [15,16]. This phenomenon is modeled by considering the particles' trajectories inside the cyclone and the probability of interparticle collisions. If some of these collisions result in effective particle agglomeration, one of the direct implications is that the particle size distribution actually processed by the gas cyclone differs from the feed size distribution, increasing the overall collection efficiency for these systems.

Upon agglomeration of fine particles by larger ones, the smaller particles will be captured as much larger particles, viz. with much higher collection efficiency than that predicted by any of the currently available models. If the cyclone is highly efficient above about 2–3 μm, i.e., above 90–95% collection, as it indeed happens with high efficiency cyclone systems, and especially with recirculation systems and numerically optimized cyclones [2,9], then the smaller particles will also be collected with these high efficiencies, and this could explain the minima observed in many grade-efficiency curves. As a direct consequence, the more efficient the cyclone

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Abbreviations: PACyc, particle agglomeration in cyclones; PSD, particle size distribuition.

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Nomenclature

a	gas entry height (m)
A	Hamaker constant (J)
b	gas entry width (m)
C	mass concentration (kg m^{-3})
c_D	drag coefficient
c_T	Lagrange constant
D	cyclone diameter (m)
D_{new}	new agglomerate diameter (m)
d_p	particle diameter (m)
$d_{p,i}$	diameter of particle i (m)
d_{trun}	cut-off diameter class
D_A	diameter of particle A (m)
D_B	diameter of particle B (m)
D_b	particle exit diameter (m)
D_C	diameter of particle C (m)
D_e	gas exit diameter (m)
$D_{final,i}$	is the last of the final diameters that belongs to class i
$D_{initial,i}$	is the first of the final diameters that belongs to class i
D_r	radial turbulent dispersion
e	energetic restitution coefficient
f	friction factor
$f(\Delta r)_i$	longitudinal correlation coefficient in direction i
f_c	collision frequency combining turbulent inertia and differential settling
f_c^{Brown}	collision frequency only by Brownian difusion
$f_{n,i}$	fraction of class i in non-cumulative number distribution
$f_{w,i}$	fraction of class i in non-cumulative mass distribution
g_i	acceleration in direction i (m s^{-2})
$g(\Delta r)_i$	tranverse correlation coefficient in direction i
H	cyclone height (m)
H_c	cyclone cylinder diameter (m)
h_z	equivalent height of cylinder gas cyclone (m)
$INFO$	structure with all identification of i particles that shifted to j class
k	turbulent kinetic energy (m^2 s^{-2})
k_B	Boltzmann constant (J K^{-1})
K	angular momentum parameter
m_{total}	total mass particle inside the gas cyclone (kg)
N_c	total number of collisions
$N_{classes}$	total number of classes
N_{final}	last of the final number of diameters belonging to a class
$n_{i,j}$	number of particles initially belonging to class i that shifted to class j
$n_{injected,i}$	number of particles of class i injected in control volume
$N_{initial}$	first of the final number of diameters belonging to a class
$n_{original,i}$	number of particles in proportion in class i
$n_{p,i}$	number of particles in class i
$n_{real,i}$	actual number of particles in class i
N_{slices}	number of slices
$N(0, 1)$	random number (standard normal distribution)
$P_{collision}$	collision probability
p_{pl}	material limiting contact (Pa)
Pe_p	radial particle Peclet number
r	radial coordinate (m)
r_w	external radius of the cyclone (m)
$R_{E,i}(\Delta r)$	Eulerian part of turbulent correlation function
$R_{p,i}(\Delta t, \Delta r)$	turbulent correlation function in direction i
$R_L(\Delta t)$	Lagrangian part of turbulent correlation function
Re_p	particle Reynolds number
Re_p^R	radial particle Reynolds number
ss	distance of the gas exit to the top of the cyclone (m)
t	instant of time (s)
T_L	Lagrangian integral time scale (s)
u_d	downward gas velocity inside the cyclone (m s^{-1})
$u_{fluid,i}$	fluid velocity component in direction i (m s^{-1})
$u_{fluid,i}^n$	fluid velocity component in direction i in time step n (m s^{-1})
$u_{fluid,i}^{n+1}$	fluid velocity component in direction i in time step $n+1$ (m s^{-1})
u_{fluid}^r	radial fluid velocity proposed by Mothes and Löffler (m s^{-1})
u_{fluid}^t	tangential fluid velocity proposed by Mothes and Löffler (m s^{-1})
$u_{fluid}^{t,*}$	tangential fluid velocity after vena contracta effect (m s^{-1})
$u_{p,i}^N$	velocity component in i direction of particle N (m s^{-1})
u_r	radial fluid velocity (m s^{-1})
$U(0, 1)$	random number (uniform distribution)
v_{cr}	critical velocity (m s^{-1})
$V_{control}$	control volume's volume (m^3)
$V_{cyclone}$	cyclone volume (m^3)
V_{fluid}	total fluid's volume in the control volume (m^3)
$V_{particles}$	total particle's volume in the control volume (m^3)
$V_{particles,injected}$	volume of the injected particles (m^3)
$x_{p,i}^N$	position of particle N in i direction (m)
z_0	contact distance (m)
α	ratio between fluid and particle volumes
β	entry parameter
Δr	displacement (m)
Δt	time step (s)
ϵ	cyclone cone angle (rad)
η_i^{final}	collection efficiency of particles belonging to class i proposed by Mothes and Löffler
$\eta_i^{final,*}$	final collection efficiency after agglomeration of a particle belonging to class i
η_i^{slice}	collection efficiency of particles belonging to class i in each slice
$\eta_j^{slice,*}$	final collection efficiency after agglomeration of a particle belonging to class j per slice
μ	fluid viscosity (kg m^{-1} s^{-1})
ϕ	collision angle (rad)
ρ	specific gravity of the fluid (kg m^{-3})
σ_F	mean fluctuation of fluid velocity at the particle position (m s^{-1})
τ	mean residence time (s)
ε	dissipation velocity of turbulent kinetic energy (m^2 s^{-3})
$\overrightarrow{u_{fluid}}$	fluid velocity (m s^{-1})
$\overrightarrow{u_{new}}$	new agglomerate velocity (m s^{-1})
$\overrightarrow{u_p^N}$	velocity of particle N (m s^{-1})
$\overrightarrow{u_{p1}}$	particle 1 velocity after collision with no agglomeration (m s^{-1})
$\overrightarrow{u_{p2}}$	particle 2 velocity after collision with no agglomeration (m s^{-1})