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Mechanism of hydrocyclone separation with water injection

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ABSTRACT

In hydrocyclones, the particle separation efficiency is limited by the suspended fine particles, which are discharged with the coarse product in the underflow. It is well known that injecting water in the conical part of the cyclone reduces the fine particle fraction in the underflow.

This paper presents a mathematical model that simulates the water injection in the conical component. The model accounts for the fluid flow and the particle motion. The stationary concentration distributions result from superpositioning the turbulent particle diffusion and particle settling. Particle interaction, due to hindered settling caused by increased density and viscosity of the suspension, and fine particle entrainment by settling coarse particles are included in the model. Water injection in the conical part of the hydrocyclone is performed to reduce fine particle discharge in the underflow. This added water transports the fine particles of the sediment to the center, where they are directed to the overflow. The model demonstrates the impact of the injection rate, injection velocity, and injection location on the shape of the partition curve. Under optimal conditions, the so-called "fish hook" of the curve is reduced without changing the cut size. The simulations are compared with experimental data of a 50-mm cyclone.

1. Introduction

One aspect of hydrocyclone development of current interest is the improvement of the separation characteristics, especially the reduction of fine particles in the coarse product (Heiskanen, 1993). One common method to address this is the injection of water in the conical part of the cyclone (Heiskanen, 1993; Patil and Rao, 1999; Kelsall and Holmes, 1990; Honaker et al., 2001; Udaya Bhaskar et al., 2004, 2005). It is assumed that this approach results in a radial fluid flow, which transports fine particles from the sediment at the cyclone wall to the cyclone center. The fine particles are then collected in the inner swirl vortex, and discharged in the overflow of the cyclone. The water injection in the conical component significantly influences the flow conditions, and it is important to implement this method so that the separation is not destroyed. The wash effect depends on the location and direction of the injection, as well as on the number of injection points and the injected water flow rate.

Research is necessary in two directions. (1) Simulation of the hydrocyclone flow with water injection. (2) Modification of existing separation models to account for the water injection. The first topic will be subject of a later contribution. This paper focuses on the second topic developing models for the modification of the partition curve of the cyclone to include the water injection.

2. Formulation of the separation model

Fig. 1a shows a scheme of the model of turbulent cross flow classification introduced by Schubert and Neeße (Schubert and Neeße, 1980; Neesse et al., 1991; Dueck et al., 2006, 2007).

The following simplifying assumptions are made:

- The main flow in the apparatus is positioned so that it crosses the direction of the separation field, i.e., the direction of the particle sedimentation with the settling velocity $V_{s,j}$ of the jth size fraction.
- The Reynolds numbers $\mathrm{Re} = U_i h/\nu$ indicate turbulent flow conditions. The turbulent particle transport is characterized by the turbulent diffusion coefficient D_t.
- At the end of the classifier, the vertical size distributions are cut at height h_u. The underflow beyond the cut off should contain the coarse particles, and the overflow should have more fine particles.
- The model is completed by the water injection not far from the apparatus end and produces a current opposite to the settling direction with the velocity $V_{in,0}$. This counter current transports the fine particles to the overflow.

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Nomenclature

c_j	*j*th fraction particle concentration
c_V	total volumetric solids concentration in suspension
d_j	*j*th fraction particle diameter, m
d_{50}	cut size, m
D_t	turbulent diffusion coefficient, m^2/s
H	height of the injection opening, m
h	height of the classifier, m
h_o	height of the overflow, m
h_u	height of the underflow, m
L	length of the apparatus, m
Δm_j	*j*th fraction particle relative concentration
$R_{o,j}$	*j*th fraction particle consumption through the overflow, kg/m^3
$R_{u,j}$	*j*th fraction particle consumption through the underflow, kg/m^3
S	split-parameter
$T(d_j)$	separation function
T_0	value of separation function for the finest fraction particles
U_i	longitudinal velocity component, m/s
$V_{in,0}$	injection rate, m/s
V_r	radial component of injection rate, m/s
$V_{s,j}$	sedimentation velocity of *j*th fraction particle, m/s
β, γ	parameters
μ_L	dynamic liquid viscosity, Pa s
ρ_p	solids density, kg/m^3
ρ_L	liquid density, kg/m^3

Subscripts

c	cyclone
i	injection
in	inlet
m	minimal
o	overflow
s	sedimentation
r	radial
t	turbulent
tan	tangential
u	underflow
0	entry

As seen in Fig. 1b, this model is applicable to the hydrocyclone. Here, in the axis-symmetrical flow, settle the particles in a centrifugal field in the radial *y*-direction. The cut off is executed by the locus of zero axial velocity between the outer and the inner vortex. In contrast to the cross flow model of Fig. 1a, the hydrocyclone overflow and underflow have opposite directions. The water injection is introduced across to the main flow at a distance H from the underflow.

This model assumes that particles are non-inertial:

$$\frac{d_j^2}{\nu} \bigg/ \frac{d_j}{|V_{in_y} - V_{s,j}|} \ll 1 \qquad (1)$$

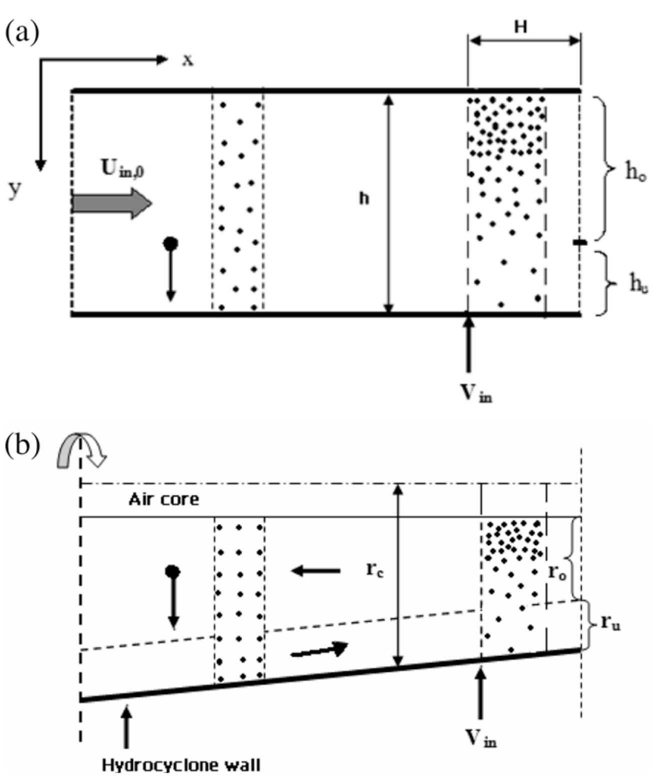

Fig. 1. Separation model of: (a) cross flow classifier, (b) hydrocyclone.

The transport equation, which describes the development of the local concentration c_j of the *j*th size fraction (particle diameter d_j) in the apparatus, is:

$$\frac{\partial U_i(x)c_j}{\partial x} + \frac{\partial}{\partial y}\left[(V_{s,j} + V_{in_y})c_j - D_t\frac{\partial c_j}{\partial y}\right] = 0 \qquad (2)$$

The boundary conditions are:

$$(V_{s,j} + V_{in_y})c_j - D_t\frac{\partial c_j}{\partial y} = 0 \quad \text{for } y = h \quad \text{and} \quad y = 0 \qquad (3)$$

The condition at the entry is:

$$c_j\big|_{x=0} = c_{j,0} \qquad (4)$$

3. Model of jet injection

Under simplifying conditions, a soft injection can be modeled as jet flowing along the bottom of the apparatus. The component of the injection velocity along the jet describes a linear function of the coordinates across the main flow in the apparatus:

$$\frac{V_{in}(x,y)}{V_{in,0}} = \begin{cases} 0, & 0 < x \leqslant L-H, \\ (-y/h)V_r, & L-H < x \leqslant L \end{cases} \qquad (5)$$

The volume conservation equation and Eq. (5) are used to determine the component of the velocity along the axis of the apparatus:

$$\frac{U_i(x)}{U_{i,0}} = \begin{cases} 1, & 0 < x \leqslant L-H \\ 1 + (V_r/U_{i,0})(x-(L-H)/h), & L-H < x \leqslant L \end{cases} \qquad (6)$$

V_r can be approximated by assuming that the injected water rate Q_{in} flows through the area of a cylinder having a diameter d_{inj} along the underflow wall. The injected water flow can be described by: $Q_{in} = \pi d_u \pi d_{in} V_r$.

It follows that: $V_r = \frac{Q_{in}}{\pi^2 d_{in} d_u}$.

4. Definition of the partition function

As shown in Fig. 1, the volume flux ratio of the overflow Q_o and underflow Q_u (volume split S) can be computed as follows: