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Original Research Paper

Process monitoring and control for constant separation conditions in centrifugal classification of fine particles

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ABSTRACT

Due to their high centrifugal acceleration tubular bowl centrifuges enable the separation and classification of fine particles. However, this type of centrifuge which is operated in a semi-continuous mode has a major disadvantage: sediment buildup in the rotor leads to a successive degradation of separation conditions over process time. In this study, a light scattering sensor was used to monitor this mechanism online by measuring the solids concentration in the overflow. Polyvinylchloride (low micrometer range) and fumed silica particles (nanometer range) served as experimental products. By incorporating the sensor signal in a control loop with the speed of the centrifuge, the mentioned drawback was compensated. As a result, grade efficiency and product loss were kept constant up to a high filling level of the rotor. It is outlined how this technology can be used for very demanding classification tasks, especially in case of fine, low-density materials.

1. Introduction

Fine particulates are becoming more and more important in particle-based products. As the desired product properties normally are a direct function of defined particle size distributions, classification is an essential process step in particle technology [1]. Especially in the micrometer range, centrifuges are a preferred tool for separating solids from the liquid phase, as they are able to achieve very high centrifugal forces. However, for sub-micron particles, continuously working centrifuges (such as centrifugal decanters or disc-stack separators) approach their limit of performance. In those cases, dispersed systems can be classified only if there is a great difference in densities between the particulate and the ambient phase [2–4]. Tubular bowl centrifuges represent the centrifuge design with the highest possible relative centrifugal force. They have been used to demonstrate that cut sizes in the sub-micron range can be achieved even if differences in density are small [5,6]. The application of this centrifuge type for classification in solids processing so far has been prevented by one major drawback: separation in tubular centrifuges is a semi-continuous process. As the processing time increases, sediment is built up in the processing chamber. As a consequence, there is less free volume available for the suspension flowing through the rotor; separation conditions gradually deteriorate as a consequence. For classification, this implies that the cut size does not remain constant but shifts towards larger particles. On the basis of model calculations, a proposal has recently been made to compensate for the negative effect of sediment buildup by adjusting the speed [7]. The necessary information about the status of sediment buildup can be determined indirectly at any point in time of the process e.g. by measuring the solids concentration in the outlet of the centrifuge.

The growing importance of online monitoring for various properties, specifically when processing colloidal suspensions, has recently been emphasized [8,9]. Not only does this technique provide means for fundamental process understanding but it also creates a good possibility for process optimization and uncomplicated scale-up. In the study presented here, a light scattering sensor is used for online monitoring of the product loss. The obtained data allow the quantification of the influence of the filling level on cut size and product loss. In addition, it is shown below how the signal of the sensor can be integrated into a control loop for the centrifuge speed in order to ensure constant separation conditions over a wide range of the filling level.

2. Theory

Whether a particle of a specific size is separated or whether it leaves the centrifuge with the overflow depends on the ratio of

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Nomenclature

Symbols

A_0	initial cross section area (m^2)
a	amplification (–)
C	relative centrifugal force (–)
FTU	formazine turbidity unit (–)
f	product loss (–)
g	gravitational acceleration (m/s^2)
n	rotational speed (min^{-1})
PVC	polyvinylchloride
$Q_3(x)$	particle size distribution; sum function weighted by mass (–)
$q(x)$	particle size distribution; density function (m^{-1})
r	radius (m)
r_{in}	inner radius, related to the liquid surface (m)
r_{out}	outer radius, related to the sediment (m)
r_{Rotor}	radius of the rotor (m)
SD	standard deviation
$T(x)$	grade efficiency (–)
t	time (s)
t_{Reset}	reset time (s)
$\dot{V}$	volume flow rate (m^3/s)
v	velocity (m/s)
$\bar{v}_{ax}$	mean axial velocity (m/s)
v_{rad}	radial velocity (m/s)
x	particle diameter (m)
$x_{T,25\%}$	particle diameter with a grade efficiency of 25% (m)
$x_{T,50\%}$	particle diameter with a grade efficiency of 50% (m)
$x_{T,75\%}$	particle diameter with a grade efficiency of 75% (m)
ε	filling level (–)
κ	classification quality (–)
λ	wavelength (m)
η	viscosity (Pa s)
ρ_l	liquid density (kg/m^3)
ρ_s	solid density (kg/m^3)
ω	angular frequency (s^{-1})
ζ	zeta potential (V)

its radial to axial velocities. Under the impact of the centrifugal field, particles are subjected to a force acting normal to the rotor axis. When applied for classification, the settling velocity has to be particle size dependent. For sufficiently diluted suspensions, the radial velocity can be approximately described by the Stokes formula:

$$v_{rad} = \frac{(\rho_s - \rho_l) \cdot x^2 \cdot C \cdot g}{18 \cdot \eta} = \frac{(\rho_s - \rho_l) \cdot x^2 \cdot \omega^2 \cdot r}{18 \cdot \eta} \qquad (1)$$

Eq. (1) is only valid for a spherical particle in a laminar sedimentation process without hydrodynamic interaction. While particle size dependent settling velocity is a requirement for classification it is not restricted to these mentioned conditions. The validity of Eq. (1) regarding the suspensions used in this work is discussed in Sections 4.1 and 4.2.

The axial velocity component (see Fig. 1) depends on the existing flow conditions. For its description two limiting cases are usually considered: The *plug flow model* assumes a constant speed over the whole cross section of the rotor constituting an idealization which cannot be observed in reality. Moreover, the liquid phase is subjected to the adhesive condition at the rotor wall while there is a much lower flow resistance at the interface between gas and liquid. Considering the case of a *boundary layer model* instead, there is a fast moving layer close to the gas/liquid interface. Below this thin layer, axial velocity is assumed to be zero. Whether the flow pattern forms a thin layer or is extended to deeper zones is determined by two opponent mechanisms: The rotating liquid is stabilized by the pressure gradient radially acting against the flow of the initial suspension. This effect is much more pronounced with increasing rotational speed. In contrast to that, a destabilization of the rotating liquid occurs by the impulse of the feed. With increasing throughput, the flow is extended to deeper zones of the rotor and is furthermore generating turbulence and back flow. This points out that flow conditions can be rather complex and depend on the interaction of operating parameters and rotor design. For a detailed overview the reader is referred to [10]. At this point, a short survey is given for experimental studies which contributed to the explanation of flow conditions in tubular bowl centrifuges. The first proof of a boundary layer was made by the addition of ink to the feed [11]. The

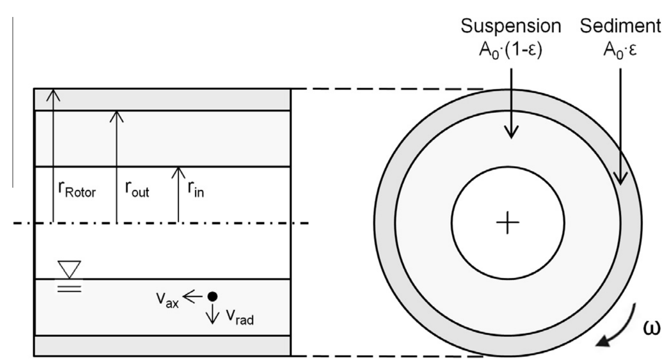

Fig. 1. Schematic segment of the rotor of a tubular bowl centrifuge.

boundary layer grew thicker with a high volume flow and a low relative centrifugal force what therefore confirmed the theoretical considerations mentioned above. These observations were proven by trend using an electrolytic marking technique [12], which is more robust methodically, while permitting more differentiated conclusions. The authors found that the liquid pool had an axial velocity component which could not be neglected. Moreover the inlet area is highly affected by turbulence leading to significant radial velocity components so that no formation of a distinct boundary layer flow is possible. The axial length of this area was found to be up to a third of the whole rotor length. An indirect experimental confirmation of those observations was later carried out by insertion of flow-influencing ring segments [13]. The smallest difference in product loss related to the original state was achieved by employing segments in the second half of the rotor which forced the liquid to flow close to the rotational axis. The rotor used in [13] is identical with the one in this work.

Furthermore sediment buildup affects the flow conditions in a complex way. As a first approximation for the separation condition of a particle in a partly filled rotor, a look at a finite rotor segment is helpful (Fig. 1). The mean axial velocity depends on volume flow as well as the cross section of the rotor available to the flow. The latter is reduced by sediment buildup.