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# Design guidelines for granular particles in a conical centrifugal filter

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ABSTRACT

Essential design criteria for successful drying of granular particles in a conical continuous centrifugal filter are developed in a dimensionless fashion. Four criteria are considered: minimum flow thickness (to ensure sliding bulk flow rather than particulate flow), desaturation position, output dryness and basket failure. The criteria are based on idealised physical models of the machine operation and are written explicitly as functions of the basket size $l_{out}$, spin velocity $\Omega$ and input flow rate of powder $Q_p$. The separation of sucrose crystals from liquid molasses is taken as a case study and the successful regime of potential operating points ($l_{out}$, $\Omega$) is plotted for a wide range of selected values of flow rate $Q_p$. Analytical expressions are given for minimum and maximum values of the three independent parameters ($l_{out}$, $\Omega$, $Q_p$) as a function of the slurry and basket properties. The viable operating regime for a conical centrifugal filter is thereby obtained as a function of the slurry and basket properties.
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*Keywords:* Design; Filtration; Centrifugation; Powders; Separation; Drying

## 1. Introduction

### 1.1. Centrifugal filters

Centrifugal filters are commonly used in the food processing and chemical industries in order to separate the liquid and solid phases of a mixture. There exist two main types of centrifugal filter: *batch* machines with a cylindrical basket and *continuous* machines with a conical basket. The present study focuses on continuous conical centrifuges, which are most commonly used in the sucrose industry to separate sucrose crystals from molasses. Swindells (1982) and Greig (1995) studied the functioning of these machines in a semi-empirical fashion. While their work provides valuable insight into the operation of conical centrifuges in the sucrose industry it does not fully address the underlying mechanics. Consequently, only a limited number of operating parameters have been used to optimize the design and operation of the sucrose machine. Application of the results for sucrose to pharmaceutical, chemical or other food products has also proved difficult.

This study aims to provide fundamental guidelines for the design of a conical centrifugal filter, based upon idealised physical models of the machine.

### 1.2. Typical operation of a continuous centrifuge

The operation of a continuous conical centrifuge is now described through the example of a typical sucrose industry machine. The rotating conical basket of the machine, sketched in Fig. 1, has a jump in cone angle along its length: a lower impervious cone has a semi-angle of $\alpha = 15^\circ$ whereas the upper perforated cone has a semi-angle of $\alpha = 30^\circ$. The basket is about 1m in diameter at outlet and spins at 1800 RPM to provide a maximum centripetal acceleration of $2000 \times g$. The inside wall of the upper, perforated cone is fitted with a slotted screen, thereby allowing for fluid drainage but preventing powder losses, see Fig. 1. The feedstock, in the form of a sucrose/molasses slurry (*massecuite*) of mass moisture fraction $M_{in} \approx 50\%$ and temperature 60°C, is introduced along the spin axis into the lower impervious cone at a constant mass flow

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**List of roman symbols**

| | |
|---|---|
| $Bo$ | bond number |
| $C_i$ | dimensionless limit for criteria $i$ |
| $K$ | Carman–Kozeny permeability empirical constant |
| $M$ | liquid mass fraction |
| $N_{cap}$ | capillary number |
| $Q$ | volumetric flow rate |
| $R$ | dimensionless radial position |
| $Ro$ | Rossby number |
| $S$ | relative saturation |
| $X_i$ | dimensionless group for criteria $i$ |
| $Z$ | ratio of fluid drainage and powder sliding velocities |
| $a$ | slip velocity dependency coefficient for wall shear traction |
| $\tilde{a}$ | dimensionless empirical slip velocity dependency parameter |
| $b$ | coefficient of friction for powder against wall |
| $\hat{b}$ | ratio of the coefficient of friction $b$ to the cone slope $\tan\alpha$ |
| $d_p$ | average particle size |
| $\tilde{d}$ | minimum through-thickness number of particles for sliding bulk flow |
| $g$ | acceleration due to gravity |
| $g^*$ | centripetal acceleration |
| $h$ | thickness |
| $k_p$ | powder permeability |
| $\tilde{k}$ | dimensionless empirical coefficient for powder permeability |
| $l_{out}$ | basket radius at outlet in cylindrical co-ordinates |
| $\dot{m}$ | total input mass flow rate of slurry |
| $n_p$ | powder porosity |
| $p$ | pressure |
| $q$ | superficial velocity of liquid through thickness of powder cake |
| $r$ | radial position in a spherical co-ordinate system |
| $s$ | particle specific area |
| $u$ | through thickness averaged radial velocity |
| $v$ | local radial velocity |
| $v_{out}$ | circumferential velocity at outlet |
| $z$ | through-thickness co-ordinate, origin $z=0$ at the wall |

*List of greek symbols*

| | |
|---|---|
| $\Sigma$ | design space |
| $\Psi$ | particle sphericity |
| $\Omega$ | cone angular velocity |
| $\alpha$ | cone semi-angle |
| $\gamma$ | fluid surface tension |
| $\zeta$ | safety factor for basket failure |
| $\theta$ | polar angle |
| $\kappa$ | ratio of permeability of screen and powder |
| $\mu_f$ | fluid dynamic viscosity |
| $\xi$ | dimensionless position of the desaturation point |
| $\rho$ | density |
| $\bar{\rho}$ | ratio of the powder density to that of the fluid |
| $\sigma$ | normal stress |
| $\tau$ | shear stress |
| $\phi$ | hoop angle |

*List of subscripts*

| | |
|---|---|
| $b$ | basket (cone) |
| $bkf$ | basket failure |
| $conv$ | fluid convected by powder movement |
| $dry$ | target dryness condition |
| $eff$ | effective |
| $f$ | fluid |
| $i$ | criteria: (1) bulk flow, (2) desaturation, (3) dryness, (4) basket failure |
| $in$ | inlet |
| $out$ | outlet |
| $p$ | powder or particle |
| $ref$ | reference value |
| $seep$ | fluid seepage through powder |
| $tot$ | total (fluid and solid) |
| $y$ | yield (of basket) |

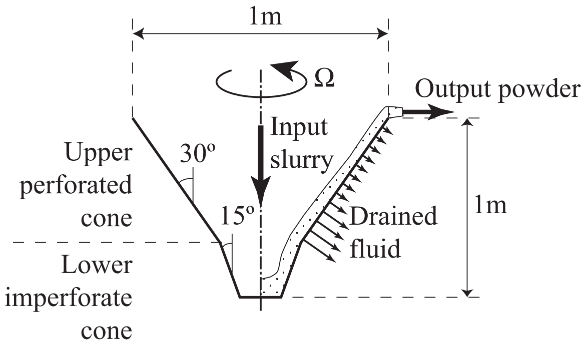


**Fig. 1 – Section of a typical continuous centrifugal filter.**

rate $\dot{m}$. The slurry acquires the angular velocity of the basket $\Omega$ and migrates up the wall of the cone under centrifugal force.[1] Sedimentation of the sucrose crystals in the lower impervious cone causes the crystals to tend to settle, and then slide, against the smooth cone wall. Three distinct regions labelled I to III can be identified in the upper perforated cone as indicated in Fig. 2a. An idealised microstructure may be assumed to exist in each region, see Fig. 2b. In region I the flow is in the over-saturated state: the sucrose crystals have settled into a densely packed layer of height $h_p$, whereas the excess fluid exists to a height $h_f > h_p$, as shown.[2]

Liquid drainage causes the slurry to evolve into an under-saturated cake of densely packed powder of height $h_p$ in region II. In region II the upper portion of the powder cake is damp and coated with a thin liquid film, while the bottom portion (of height $h_f$) is still saturated with fluid. Finally in region III, providing the centripetal acceleration is sufficient to overcome capillary forces, the powder is desaturated and only a residual liquid fraction wets the surface of the crystals. The flow in

[1] Most of the tangential acceleration occurs in an acceleration cone which deposits the slurry onto the lower impervious cone at an angular velocity already close to $\Omega$.

[2] Here we assume complete initial settlement of the solid phase occurs in the lower impervious cone. In a previous study (Bizard and Symons, 2011) we have compared this assumption with the other extreme of nil settlement at the start of region I. The effect on the downstream regions II and III was found to be negligible.

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