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The application of mini-hydrocyclones in the concentration of yeast suspensions

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Abstract

Small diameter hydrocyclones have had an increasing use in performing difficult separations between phases, due to the large centrifugal forces generated in them. The potential use of hydrocyclones in the concentration of microbial suspensions is attractive as they are continuous, high capacity devices requiring low maintenance while having the additional benefit in that they can be readily sterilised.

Results are reported on the de-watering of Bakers' yeast in a 10 mm diameter hydrocyclone to quantify the separation process. The form of the model equation for recovery has been derived based on the non-equilibrium residence time theory. This is shown to represent experimental data in that increasing pressure and temperature exhibit a positive effect on both the recovery and the concentrating effect while an increase in the feed concentration exhibits a negative effect on these. In addition, the influence of cyclone geometry on the recovery and concentration ratio has been illustrated. Increasing the vortex diameter results in an increasing concentration ratio and a decreasing recovery. Increasing the diameter of the spigot shows the opposing trends.

Typical results from a single stage separation combine a recovery of 60% with a concentration ratio of 1.25 and a recovery of 30% with a concentration ratio of 2.0. Concomitant improvement of the recovery and concentration ratio will be attainable through the use of multi-stage hydrocyclone circuits.

Keywords: Mini-hydrocyclones; Yeast suspension; Microbial cells

1. Introduction

The separation of microbial cells from the culture medium is required in most microbial processes, regardless of whether the desired product is the cell itself, an intracellular or an extracellular compound. The challenge of these separations is the small particle size (typically 1–10 μm in diameter), the low density difference with respect to the suspending medium, the heat labile nature of many products and the non-newtonian, concentration-dependent rheology of the concentrated cell suspensions.

Most commonly used separation processes include filtration or high speed centrifugation. Centrifuges and cyclones function on the same principle of magnified centrifugal field to effect a separation between solids and liquids, solids of different sizes or different liquids. Traditionally, hydrocyclones function at lower centrifugal fields than centrifuges. However, by decreasing the diameter of the hydrocyclone, the centrifugal fields produced can be increased. For example, fields in the range 10 000–50 000 g can be produced in a 10 mm diameter hydrocyclone at a capacity of approximately 150 l h^{-1} [1]. In this study, the use of small diameter hydrocyclones is investigated owing to their potential as continuous, high capacity devices that require low maintenance and are readily sterilised.

Fig. 1 shows the essential features and flow pattern within a hydrocyclone. The feed slurry enters the hydrocyclone tangentially, resulting in a primary vortex flow moving downward and a secondary vortex of smaller diameter, moving upward. Solids are, due to the large centrifugal forces, forced into the outer vortex and exit the cyclone at the spigot as the concentrated underflow. The inner vortex forms the overflow, consisting primarily of the fluid, and exits the cyclone through the vortex finder. While the diameter of the cylindrical section of the cyclone is a major variable determining the size of particle that can be separated, the diameters of the vortex finder and spigot can be varied to alter the separation [2].

This study sets out to quantify the performance of mini hydrocyclones for the separation of microbial cells from sus-

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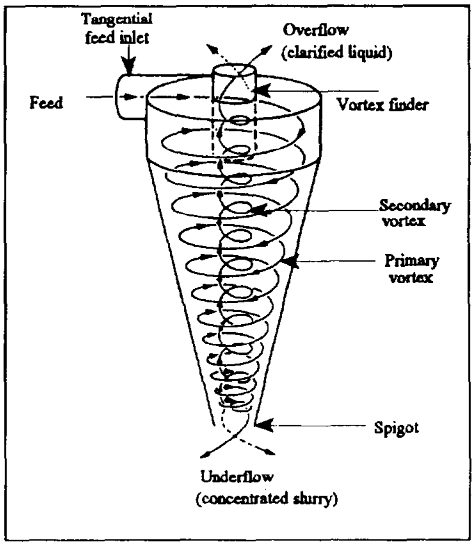

Fig. 1. Essential features of the hydrocyclone.

pension, as modelled by yeast. Experimental studies are supported by the development of a theoretically-based model. Previous work [3] reported on this separation. That study is extended here to consider the effects of pressure, temperature, feed concentration and hydrocyclone geometry, and to expand on the data interpretation and modelling in terms of the theory of the separation mechanism. Rickwood et al. [4] first explored this separation, and indicated the feasibility of using small diameter hydrocyclones. Further work [5] investigated the effect of hydrocyclones on cell breakage.

2. Theories of separation

2.1. Equilibrium orbit theory

The flow profile in a hydrocyclone is different to that in a centrifuge, in that a free vortex rather than a forced vortex is formed. The tangential velocity of the fluid increases toward the centre of the hydrocyclone, resulting in greater centrifugal forces on the particles toward the centre. Furthermore, there is a radial fluid velocity toward the centre of the cyclone, decreasing as the radius decreases. A balance between these forces indicates that a particle within a hydrocyclone may find an equilibrium orbit position. Smaller particles are found toward the centre, larger particles toward the outside. As the inner fluid vortex is moving upwards toward the vortex finder and the outer vortex downward toward the spigot, small particles will find themselves within the inner vortex, larger particles in the outer and will be collected in the respective outlets. It is, however, unlikely that a particle will reach its equilibrium position during the relatively short residence time within the mini-hydrocyclone (of the order of 0.03 s at a flowrate of 150 l h^{-1}), and a mathematical description based on residence time is considered to be more appropriate for modelling hydrocyclone performance.

2.2. Non-equilibrium (residence time) theory

In contrast to the equilibrium orbit theory, the residence time theory [6] considers whether a particle entering the cyclone will traverse the inlet diameter, D_i, and reach the cyclone wall (and hence report to the underflow) in the residence time, τ. This treatment assumes that settling is described by Stokes' law without turbulence or inertial effects, and that no hindered settling occurs. A particle of size d_p, in a centrifugal field, will settle at its terminal settling velocity in a radial direction, u_r, according to

$$u_r = \frac{(\rho_s - \rho) d_p^2 \nu_r^2}{10 \mu r} \tag{1}$$

For a mono-sized feed, the fractional recovery of particles to the underflow can be described by

$$R = \frac{\int_0^\tau u_r \, dt}{D_i} \tag{2}$$

The static pressure drop equals the centrifugal head

$$\Delta P_s = \int_0^{D_c/2} \rho \frac{\nu_t^2}{r} \, dr \tag{3}$$

Since the axial velocity

$$\nu_z = \frac{dz}{dt} \tag{4}$$

and assuming that the flow near the wall follows the wall contour

$$\frac{dz}{dr} = 2 \frac{L}{D_c} \tag{5}$$

the equations can be combined to yield

$$R = \frac{d_p^2 (\rho_s - \rho)}{9 \rho D_i} \frac{L}{D_c} \frac{\Delta P_s}{\nu_z} \frac{1}{\mu} \tag{6}$$

For a given geometry, the volumetric throughput, Q, of the hydrocyclone is related to the total pressure drop, ΔP, by

$$Q = k \, \Delta P^{0.5} \tag{7}$$

which is in agreement with the theoretical prediction of flow through a pipe [1]. Also,

$$Q = \frac{\pi}{4} D_i^2 \nu_i \tag{8}$$

For efficient hydrocyclones the difference between the static and total pressure drop is small [6], and the equation for recovery can be written as

$$R = \frac{k d_p^2 (\rho_s - \rho)}{36 \rho} \frac{L \pi D_i \nu_i}{D_c \nu_z} \Delta P^{0.5} \frac{1}{\mu} \tag{9}$$

At high Reynolds numbers, the ratio of the inlet to axial velocities can be assumed to be constant for a given hydrocyclone geometry [6], and the equation can be reduced to:

$$R = k_{\text{particle}} k_{\text{geometry}} \, \Delta P^{0.5} \frac{1}{\mu} \tag{10}$$

3. Experimental methods

3.1. Microbial suspension

In this study, *Saccharomyces cerevisiae* (Bakers' yeast) was used as a model suspension. Suspensions were obtained from Anchor Yeast (Epping, Cape Town) as yeast cream. The cells showed a narrow size distribution. The dominant diameter was measured as 5.5 μm by laser light scattering and 4.5 μm from the settling velocity. Reported densities vary from 1072.5–1095.2 kg m^{-3} [7]. The yeast was resuspended at the required concentration in physiologically buffered saline solution. Under these nutrient depleted conditions, metabolic activity will be low.

3.2. The hydrocyclone

A 10 mm Mozley solid-liquid hydrocyclone connected to a 1.1 kW pump (Mono) was used. The hydrocyclone was fitted with a spigot of diameter 1.0 or 1.5 mm and a vortex finder of 2.0, 2.6 or 3.2 mm as specified, and had an internal length of 41 mm. The outlets were open to the atmosphere, and allowed an air core to form in the cyclone. The suspension was maintained at a constant temperature of 21 °C in a constant temperature waterbath.

3.3. Analytical methods

Timed samples of 30 s were taken simultaneously from the over and underflow streams of the hydrocyclone. These samples and a sample of the feed were weighed, dried and the yeast concentration of the feed, overflow and underflow streams determined gravimetrically.

The absence of cell breakage was confirmed by the measurement of the soluble protein release [8] and microscopic observation. This is in agreement with the findings of Rickwood et al. [4]. The effect on cell metabolic activity and viability [5] were not investigated in this study.

4. Results

Fig. 2 shows the relationship between the flowrate and the pressure drop across the cyclone.

The results show that the expression given in Eq. (8) accurately describes the flowrate–pressure relationship in the cyclone. At 700 kPa, the throughput rate, depending on the outlet diameters used, ranges from 100–150 l h^{-1} (28–42 ml s^{-1}).

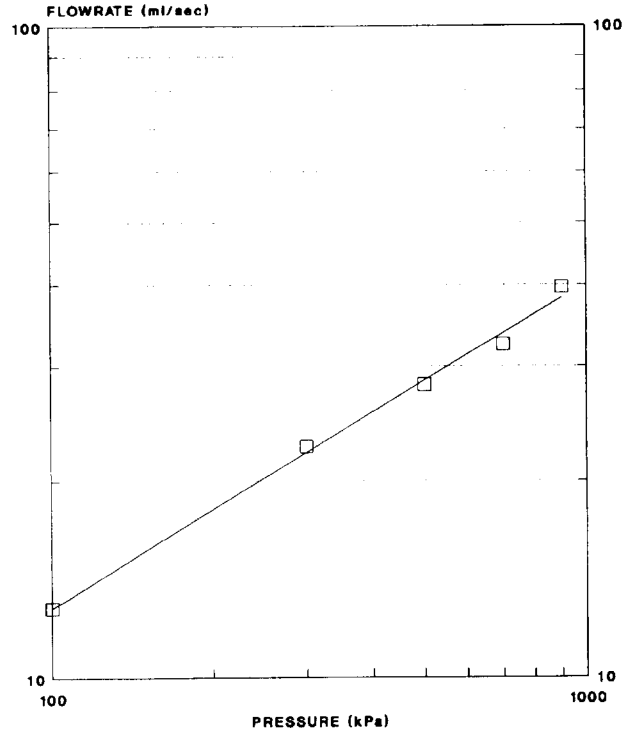

Fig. 2. The effect of operating pressure on the hydrocyclone throughput rate. (18 g l^{-1}, 21 °C, 1 mm spigot, 2 mm vortex finder.)

The separation in a hydrocyclone between solids and liquids is incomplete. A fraction of the solids reports to the vortex finder rather than the spigot, and a fraction of the water in the feed reports to the concentrated underflow stream. Thus quantifying the performance requires two values; the recovery of solids from the feed to the underflow, R, and the concentration ratio, C, the ratio of the concentrations of the underflow and the feed. Both R and C are to be maximised. The ratio of these two values yields the volumetric recovery of suspension to the underflow, R_v, which should be minimised. For hydrocyclones with both outflows emerging into ambient pressure, as in this case, R_v is not controllable. Ideally, the ratio of the overflow concentration to the feed concentration should be zero.

Fig. 3 shows the effect of operating pressure on the separation achieved, treating a yeast suspension of 18 g l^{-1} at 21 °C. There is a positive effect of pressure on both the recovery and concentration ratio. This decreases at high pressures. A poor concentration ratio is observed below 300 kPa.

The effect of yeast concentration in the feed to the cyclone at constant temperature (21 °C) and pressure (700 kPa) is shown in Fig. 4. It can be noted that as the feed concentration is increased, both the recovery of solids to the underflow and the concentration ratios are decreased. The flow ratio, R_v, is largely unaffected by the feed concentration and has a value of approximately 18%.

Fig. 5 shows the effect of the operating temperature on the performance of the cyclone. It can be noted that both the recovery and the concentration ratio increase with an increase

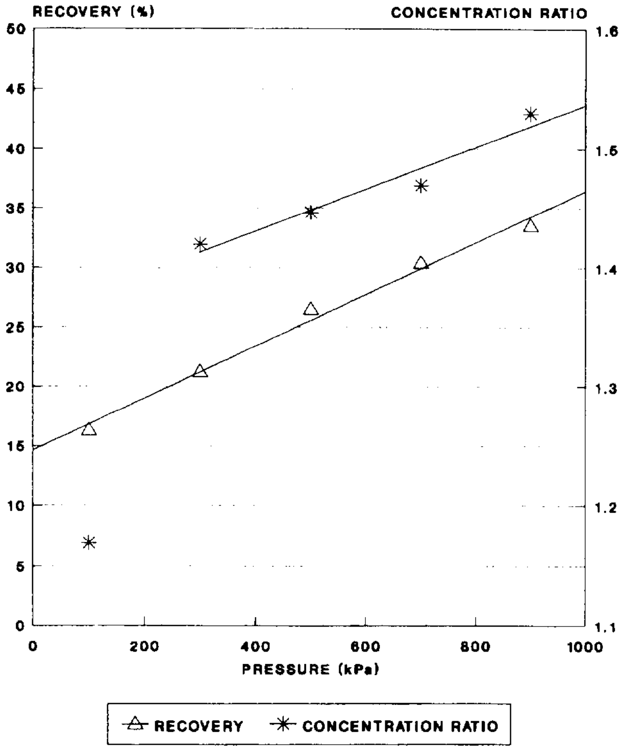

Fig. 3. The effect of operating pressure on recovery and concentration ratio. (18 g l^{-1}, 21 °C, 1 mm spigot, 2 mm vortex finder.)

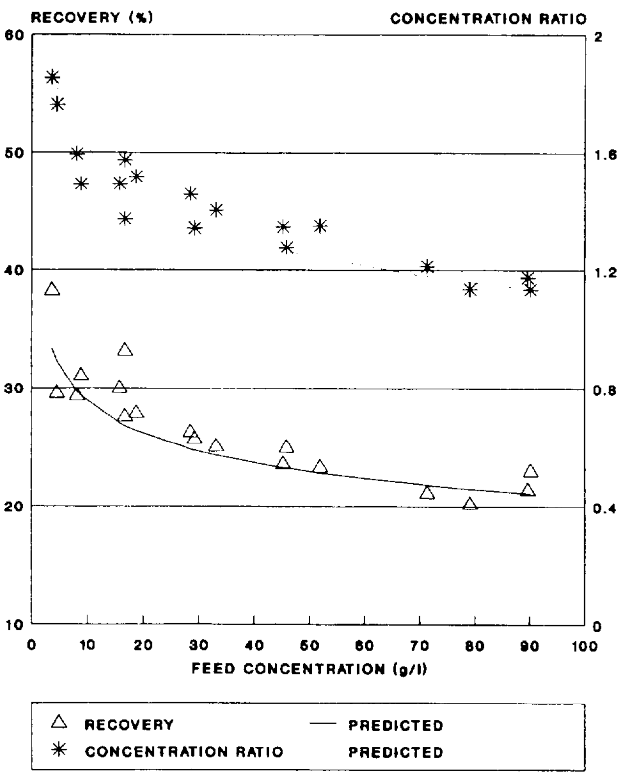

Fig. 4. The effect of feed concentration on recovery and concentration ratio. (700 kPa, 21 °C, 1 mm spigot, 2 mm vortex finder.)

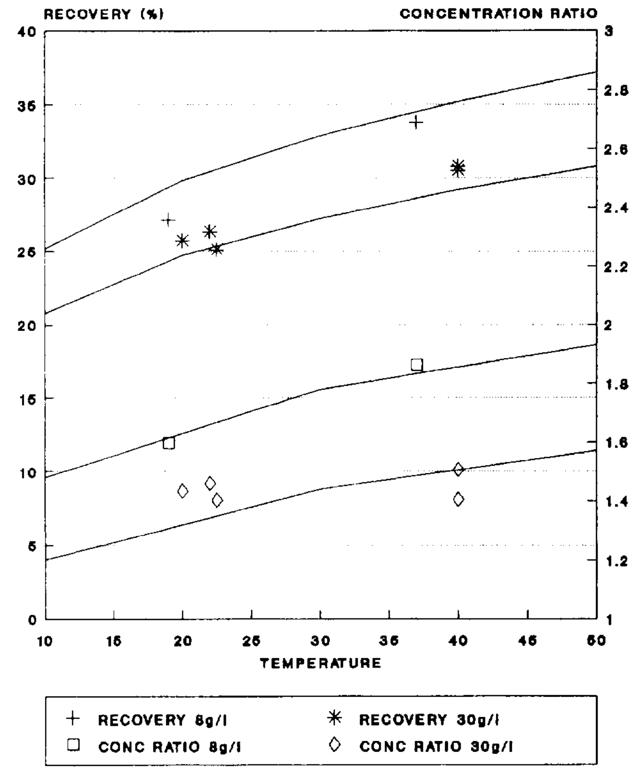

Fig. 5. The effect of temperature on recovery and concentration ratio. (18 g l^{-1}, 700 kPa, 1 mm spigot, 2 mm vortex finder.)

in temperature. A comparison of the data at different feed concentrations suggests an interaction between the temperature and the feed concentration, in both instances. The positive effect of temperature on the separation is reduced at high feed concentrations.

The effect of cyclone geometry has been investigated. On increasing the spigot diameter from 1 to 1.5 mm, the capacity increased from 34 to 45 ml s^{-1} at 700 kPa and 21 °C, with a feed concentration of 18 g l^{-1}. In addition, the recovery of yeast to the underflow increased by twofold, while the concentration ratio decreased by 50% across the concentration range shown in Fig. 4. Simultaneously increasing the vortex finder diameter, as shown in Fig. 6, increases the concentration ratio with a concomitant decrease in the recovery. On increasing the vortex finder diameter to 3.2 mm, the throughput increased to approximately 60 ml s^{-1}. It can be seen from Fig. 6 that the effect of an increase in the vortex finder diameter is reduced at large vortex finer diameters.

5. Discussion

Eq. (10), repeated here,

$$R = k_{\text{particle}} k_{\text{geometry}} \, \Delta P^{0.5} \frac{1}{\mu} \tag{10}$$

has been derived on a theoretical basis by the employment of non-equilibrium residence time theory. It should be noted that the viscosity term in this expression, μ, is a function of the viscosity of the suspending fluid under standard conditions, μ_s, the temperature of the suspension, T, and the solids concentration in the suspension, c. The change of the viscos-

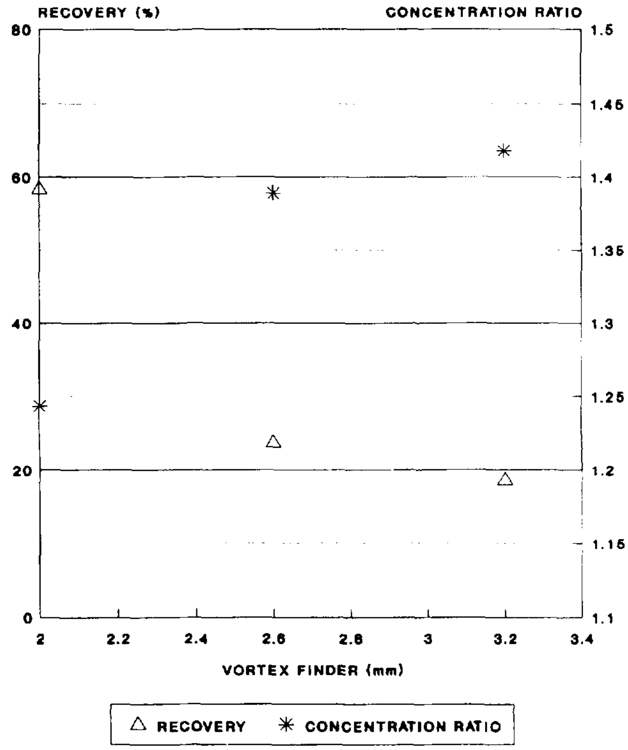

Fig. 6. The effect of vortex finder diameter on cyclone performance. (15 g l^{-1}, 21 °C, 700 kPa, 1.5 mm spigot.)

ity of water as a function of temperature is well established [9] and expressions for the viscosity of yeast suspensions as a function of temperature have been reported [7]. To date no expressions have been developed that describe the simultaneous effect of temperature and yeast concentration on the viscosity of the suspension.

Based on the experimental data, the following function is assumed to describe the suspension viscosity:

$$\mu = k\mu_s T^{-\alpha} c^{\beta} \tag{11}$$

As the viscosity of the suspending medium has not been varied in these studies, μ_s (under standard conditions, i.e. constant temperature) can be considered constant and the effect of temperature on the viscosity is taken into account by the temperature term in the equation. Hence Eq. (11) can be modified to:

$$R = k\Delta P^{0.5} T^{\alpha} c^{-\beta} \tag{12}$$

Eq. (12) has been fitted to the experimental data obtained using a 1 mm diameter spigot and a 2.6 mm diameter vortex finder by linearisation and least squares regression. The resultant relationship can be used to predict recovery for this hydrocyclone geometry:

$$R = 1.391\ \Delta P^{0.402} T^{0.243} c^{-0.143} \tag{13}$$

Note that the units are percentage for R, kPa for ΔP, °C for T and g l^{-1} for c, with the constant ensuring consistency. The positive exponent of temperature is in accordance with the theoretical prediction, owing to the inverse relationship between temperature and viscosity. The negative exponent of the feed concentration is in accordance with the negative effect of viscosity on recovery. Possible interactions of temperature and concentration effects on recovery, suggested by Fig. 5, have been accounted for in the model form. The reduced value of the exponent of pressure with respect to the predicted value of 0.5 may be attributed to hindered settling in the regions of high solid concentrations in the hydrocyclone. The goodness of fit of the regression is shown by the solid lines in Figs. 4 and 5.

No theoretical guidance could be found for the corresponding relationships of either the concentration ratio or the volumetric recovery. However, it can be deduced that the volumetric throughput, Q, for a given cyclone, is a function of the operating pressure and the viscosity:

$$Q = f(\Delta P^{0.5}, \mu) \tag{14}$$

If it is assumed that this form is suitable for the volumetric flowrate of the underflow, Q_u, it can be used to describe the volumetric recovery, R_v, where

$$R_v = \frac{Q_u}{Q} \tag{15}$$

Hence this form is applicable to the concentration ratio C since

$$C = \frac{R}{R_v} \tag{16}$$

The following relationships are thus derived from the experimental data generated by using a spigot with a diameter of 1 mm and a diameter for the vortex finder of 2.6 mm:

$$C = 0.859\ \Delta P^{0.074} T^{0.168} c^{-0.158} \tag{17}$$

$$R_v = 1.619\ \Delta P^{0.328} T^{0.075} c^{0.015} \tag{18}$$

The fit of the regression describing the concentration ratio data is shown in Fig. 4. Note that the effect of temperature and concentration on the volumetric recovery is small, as has been previously reported [3].

6. Conclusion

The feasibility of attaining separation of microbial cells from the culture suspension using a 10 mm hydrocyclone has been illustrated. No disruption of the yeast cells was observed in the cyclone. The recovery of cells to the underflow and the concentration ratio attained are a function of the operating pressure, temperature, feed concentration of the suspension, spigot diameter and diameter of the vortex finder. A theoretically-based equation has been developed to describe the recovery as a function of operating pressure and viscosity in terms of pressure, temperature and feed concentration. This treatment has been extended to provide a relationship for the concentration ratio and volumetric recovery of the same form.

It has been shown that for a single stage hydrocyclone, the simultaneous achievement of acceptable recovery levels and concentration ratios is favoured when treating low feed concentrations. However, design of an appropriate hydrocyclone circuit will permit the concomitant improvement of recovery and concentration ratio at higher feed concentrations.

Nomenclature

c	solids concentration of feed suspension
C	concentration ratio
d_p	particle diameter
D_c	cyclone diameter
D_i	inlet diameter
k	constant
L	length of cyclone
ΔP	operating pressure
ΔP_s	static pressure drop
Q	volumetric flowrate in feed
Q_u	volumetric flowrate in underflow
r	radial position
R	fractional recovery of solids to underflow
R_v	fractional volumetric recovery of suspension to the underflow
t	time
T	temperature
u_r	particle terminal velocity in radial direction
v_i	inlet fluid velocity
v_t	fluid velocity in tangential direction
v_z	fluid velocity in axial direction
z	axial position

Greek letters

α, β	constants
ρ	density of suspending medium
ρ_s	density of solid particle
μ	viscosity of suspension
μ_s	viscosity of the suspending medium
τ	residence time

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