Optimising Decanter Centrifuges

By F Reif & W Stahl
Institut für Mechanische Verfahrenstechnik und Mechanik, Universität Karlsruhe, Postfach 6980, D-7500 Karlsruhe, West Germany
and T Langeloh
Bokela Ingenieurgesellschaft für Mechanische Verfahrenstechnik mbH, Haid und Neu Straße, D-7500 Karlsruhe, West Germany

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Three fundamental problems are involved when dealing with decanter centrifuges: these are, in particular, clarification, dewatering and whether or not the conveyance of the solids is guaranteed at all. To the latter, the torque and the power consumption are closely related. All single problems have been solved by the authors recently. In the present project the steps are combined to show how the functioning of a decanter can be improved, which leads to an increased efficiency of this type of centrifuge. Further it will be indicated that optimisation has to consider the specific demands made on the machine and the product.

In the first part the different models valid for crystalline products are introduced and in the second, the most important results, ie the influences of the design and operation, are presented.

DECANTER CENTRIFUGES are used for solid-liquid separation, thus they must clarify the liquid and dewater the solids. For both tasks a functioning conveyance of the solids is a presupposition. Since the transportation is influenced by the sedimentation and by the dewatering of the solids and vice versa, all three problems must be considered together to be able to predict the clarification as well as the dewatering result. Furthermore, the necessary torque and the power input can be calculated, whereby the latter is essential for the running costs of the apparatus. The power consumption and the transport torque are also closely related to the destruction and overheating of the product.

Thus, in this presentation the theory for the clarification, the dewatering and the solids conveyance must be introduced shortly. Although the models deal mainly with crystalline products, parallels to sludges can be drawn. Showing the influences of the design and operational parameters, it is indicated that the optimisation depends on the specific product and on the demands of the operator.

Even though this paper deals with counter-current decanters, it is nevertheless applicable to other co-axial screw-feed centrifuges, eg worm-screen centrifuges or screen decanter centrifuges.

The two main intentions are to enable the operator in industry to improve the functioning of the decanter or to overcome difficulties which arise, and to decry the popular idea which looks on the centrifuge as a black box hardly taking into account the product and the needs.

Construction and Operation of Decanter Centrifuges

The method in which a counter-current decanter works shall be explained shortly. A very explicit description, also of other scroll type centrifuges, has been previously published(1).

The suspension is pumped into a hollow screw conveyor shaft, in which it is extensively pre-accelerated before it flows through the compartment outlets into the actual process chamber, the drum. As a result of the centrifugal field, the fluid assumes the form of a hollow cylinder, its wall thickness being determined by the adjustable height of the weir outlet, also known as the pool or pond surface level h_{pond}.

While the liquor flows along the screw towards the outlet, the solids settle down; thus the application of the centrifuge is practical only in cases where the density of the solids contained within the suspension is higher than that of the mother liquor. Subsequently the bulk is transported by the screw conveyor, which rotates at a differential speed of n_{Diff} relative to the drum, up the cone; here, the solids dewater. The most important dimensions of a decanter centrifuge are shown in Fig 1; also included are the cone angle β and the blade angle Γ.

The screw angle α is defined as:

$$\alpha = \arctan\left(\frac{G}{2\pi R_l}\right) \tag{1}$$

where: R_l = local bowl radius.

Theory

Here the three fundamental aspects, dewatering, clarification and conveyance, are introduced.

Clarification. The clarification in decanter centrifuges is influenced in principle by the sedimentation of the particles and by their entrainment with the outflow of the centrate. An effect of the solids conveyance due to a backflow down the cone is out of question in case of separating coarse, crystalline products and of a proper design of the scroll.

As already explained(2-4), the theory of the equivalent clarification area Σ says simply that the settling area in a decanter, A, is enlarged by the C-value, the multiple of the earth acceleration, ie Σ is defined as:

$$\Sigma = A \star C \tag{2}$$

with:

$$A = 2\pi R_{cyl} L_{cyl} \tag{3}$$

$$C = \frac{\Omega^2 R_{cyl}}{g} \tag{4}$$

Considering sedimentation as the only relevant physical process, leads to a maximum volume flow rate of:

$$\dot{V}_{Sus,\,max} = w_{sed} \star \Sigma \tag{5}$$

with the Stokes settling velocity:

$$w_{sed} = \frac{(\rho_s - \rho_l)\, x^2\, g\, C}{18\, \eta} \tag{6}$$

At the maximum flow rate, particles smaller than x are not settling in time, ie these solids are discharged with the liquid, if the flow rate is higher than $\dot{V}_{Sus,\,max}$.

The equivalent clarification area is mainly used for the scale-up of decanter centrifuges. But cases exist where the actual result is worse than that predicted, because the sediment is carried away at high flow rates or velocities by the liquid, which flows through the channel formed by the screw blades.

This phenomenon can be described by the drag effect(4, 5). In an analogy to the equivalent clarification area, the drag value D can be used as a characteristic number for the scale-up of decanter centrifuges. The drag value can be calculated from the geometrical data of the screw together with the C-value and is defined by:

$$D = \frac{(G \cos\alpha \star h_{pond})^{8/7}}{(G \cos\alpha + 2\, h_{pond})^{1/7}} \star C^{4/7} \tag{7}$$

If the drag effect limits the volume flow rate, it can be determined by:

$$\dot{V}_{Sus,\,max} = \left(\frac{x\, \mu' \,(\rho_s - \rho_l) \star 1.7\, g}{\rho_l^{0.75} \star \eta^{0.25}}\right)^{4/7} \star D \tag{8}$$

Summing up, it may be said that a particle is separated in a decanter, if it settles down to the channel ground during its residence time and if the shear of the flow is smaller than the frictional or adhesive forces, which hold the particle in the sediment. The result of the clarification can be expressed in terms of the recovery, which represents the fraction of separated particles.

Dewatering. The following model is used to describe the basics of dewatering. In the product cake two different regions can be recognised(6, 7): in the lower one, up to a particular height f, the product cake is completely saturated, ie the voidage is totally filled up with liquid; thus the saturation S, defined as the ratio of liquid volume to voidage, is equal to unity. Since the upper one contains only the remaining equilibrium and the time dependent film liquid, the saturation can be approximately expressed(8, 9) for this part of the product by:

$$S = S_\infty + \frac{4}{3}\sqrt{\lambda} \tag{9}$$

with:

$$\lambda = \frac{4\, \eta\, (h - f)}{\rho_l\, g\, C\, d_h^2\, t} \tag{10}$$

In the above equation t is the time which the cake needs to be conveyed to the particular location on the cone. The equilibrium saturation S_∞ can be set constant over a wide range of operating conditions as long as not too fine particles and too low centrifugal fields are considered. Otherwise the capillary height has to be taken into account. The weighted average of both regions yields the total saturation of the cake at a particular location on the cone. It should be pointed out that f as well as the saturation of the second region (Eq (9)) changes with the location but not with time.

The trend of the film height or of the interface between both regions is obtained by using Darcy's law. It can be shown that f decreases linearly. It vanishes exactly at the cone end, if the specific throughput $\dot{m}_s^+$ is reached. Of course $\dot{m}_s^+$ depends on the geometry

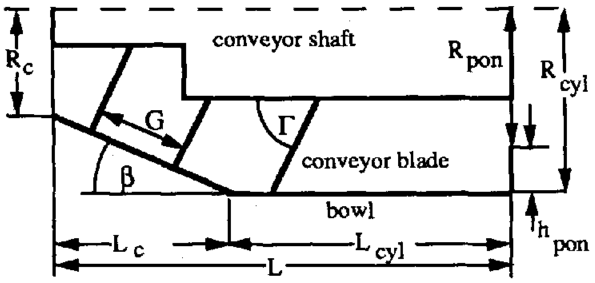

Fig 1. The important dimensions of a decanter centrifuge

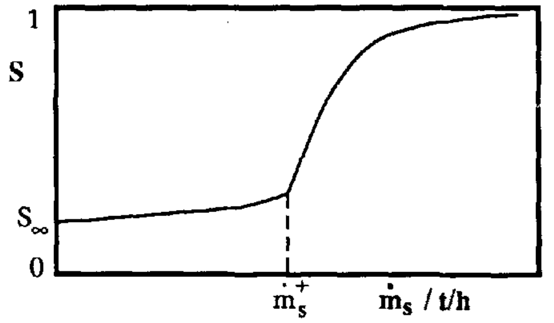

Fig 2. Typical trend of saturation vs solid mass throughput

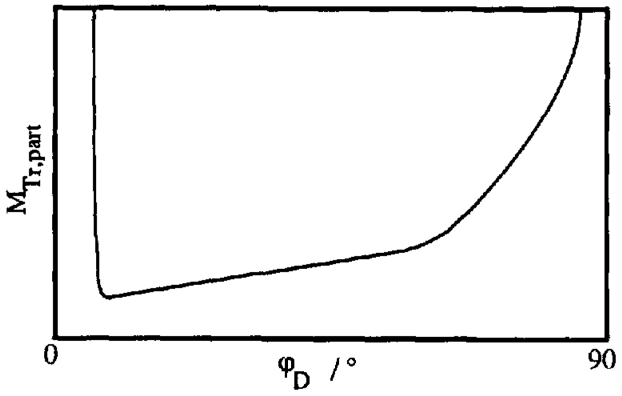

Fig 3. Partial transport torque vs the frictional angle of the bowl

and the operating conditions, eg the following equations can be derived:

$$\frac{\dot{m}_s^+}{\dot{m}_{s,0}^+} \approx \left(\frac{C^+}{C_0^+}\right)^{\frac{2}{7}} \approx \left(\frac{t_{tot}}{t_{tot,0}}\right)^{\frac{2}{7}} \approx \left(\frac{n_{Diff,0}}{n_{Diff}}\right)^{2}$$

$$\approx \left(\frac{s}{s_0}\right)^{\frac{2}{7}} \approx \left(\frac{\sin\alpha}{\sin\alpha_0}\right)^{\frac{2}{7}} \approx \left(\frac{\sin\beta}{\sin\beta_0}\right)^{2} \qquad (11)$$

$$\dot{m}_s^- - \dot{m}_{s,0}^+ \sim (R_{pon,0}^2 - R_{pon}^2) \qquad (12)$$

Using this model, a typical trend of the saturation vs the mass throughput$^{(10)}$ is obtained as shown in Fig 2. For small loads the saturation increases very slightly; it consists only of the equilibrium and of the film liquid. For mass throughputs higher than the specific throughput $\dot{m}_s^+$, the liquid content augments very steeply, because part of the discharged product cake is still completely saturated.

Conveyance. By a force balance and by the condition of steady contact between product and bowl or scroll, the velocity of the product cake and its residence time as well as all single forces are determined. This force balance contains the centrifugal, the normal and frictional forces as well as the fluid forces. It can be shown that the Coriolis force can be neglected. It causes only the inlet stream to be accelerated towards the liquid outlet with trailing scrolls and towards the solids outlet with forwarding scrolls. In the first case, the conveyor scroll rotates at a lower speed than the bowl, and the sedimentation is deteriorated; in the second case, dewatering results.

After obtaining the forces, the transport torque and transport power consumption can be calculated. If the partial transport torque $M_{Tr,part}$ is plotted vs the frictional angle at the bowl, a typical trend can be observed, as shown in Fig 3. At low frictional angles a further decrease results in a steep increase of $M_{Tr,part}$, since here the product is only circumferentially conveyed, so that mass accumulates inside the decanter.

At even lower angles, the product would slip down the cone back into the cylindrical part of the decanter, therefore, at this steep increase and left of it, no conveyance is possible. After passing the

Table 1. General trends in decanter centrifuges

Results	Recovery	Moisture content	Conveyance	Specific Throughput	Torque	Power-consumption	Product destruction
Product Parameter							
Particle size	↑	↓	↗	↑	↘	→	→
Dynamic viscosity	↘	↗	→	↘	↗	–	–
Surface tension	–	↗	↘	–	↗	→	→
Solid density	↗	–	–	–	–	–	–
Liquid density	↘	↘	–	↗	o	o	–
Operational Parameter							
Throughput	↘	↗	o	–	↗	↗	↗
Solids concentration	↘	–	–	–	↗	↗	–
C-value	↗	↘	↗	↗	↗	↗	↗
Differential speed	↘	→	↘	→	↘	→	↗
Pool level	↗	↗	→	↘	↘	→	↘
Design paramters							
Cone angle	–	↘	↘	↗	↗	→	↗
Screw angle	↗	↘	o	↗	o	o	o
Blade angle	–	–	o	–	o	o	o
Cylinder length	↗	–	–	–	↗	↗	→
Cone length	–	↘	↘	↗	↗	↗	↗
Clearance	–	↘	↗	↗	↗	→	↗
Profiled cone	–	–	↗	–	↗	↗	↗
Trailing scroll	↘	–	–	–	↗	→	→
Forwarding scroll	–	↗	–	–	–	–	–

minimum, a raise in the friction yields, of course, an augmenting torque.

The product of torque and differential angular speed yields the power consumption:

$$P_{Tr,part} = M_{Tr,part}\,\Omega_{diff} \qquad (13)$$

The transport torque may be regarded as a direct measure for the product destruction, while the transport power, which is completely converted into heat, contributes additionally to the overheating. The resulting mean temperature increase can be determined by an enthalpy balance; thus the danger of overheating is reduced with higher moisture contents because of the relatively high latent heat of the liquids. For the selection of the proper gear and drive unit, the transport torque and transport power are not important but their total values, for which an acceleration term has to be added:

$$M = M_{acc} + M_{Tr} \qquad (14)$$

$$P = P_{acc} + P_{Tr} \qquad (15)$$

The acceleration torque(11) is calculated by a momentum balance(12), ie:

$$M_{acc} = \dot{m}\,\Omega\,R_{pon}^2 \qquad (16)$$

and:

$$P_{acc} = \dot{m}\,\Omega^2\,R_{pon}^2 = M_{acc}\,\Omega \qquad (17)$$

It is important to note that contrary to Eq (13) the acceleration power and torque are formed by the total mass throughput; therefore savings can be made by concentrating the suspension in a pre-thickener. Further is the power obtained by multiplying the torque with the angular speed of the drum, which is about two dimensions greater than the differential speed. This is the reason why the acceleration term contributes only a small portion to the total torque, but a large one to the total power requirement.

An effective density integrates the effects of the fluid forces, ie of the buoyancy and the resistance force. Immediately it is clear that a high pool surface level increases buoyancy thus decreasing the torque, whereas small particles enhance the resistance increasing the torque and power consumption.

As frictional forces along the scroll and bowl exist, the friction coefficient μ:

$$\mu = \tan\varphi \qquad (18)$$

has to be considered, and can be calculated, at least as a first approximation, by:

$$\mu = \mu_0\left(1 + \frac{N_{Br}}{N}\right) \qquad (19)$$

with μ_0 as dry and wet friction coefficient, N the normal force and N_{Br} the sum of all fluid bridge forces within the sheared zone(13), whereby the single bridge force is proportional to the ratio of the surface tension to the particle diameter. For particles not too smooth, the maximum of the friction coefficient is found close to the equilibrium saturation $S_{Br,i}$. In the region where the dewatering already took place, ie the upper region, this maximum is the valid value. In the lower, ie in the totally saturated region, μ_0 has to be taken. The following general statements result then from the above equation:

☐ The friction coefficient is usually higher at the scroll than at the bowl, which deteriorates the ability for the conveyance;
☐ With increasing centrifugal acceleration and mass throughput the friction coefficient decreases;
☐ As long as the product is below the pool level, low friction coefficients arise;
☐ Worse dewatering behaviour usually results in lower friction coefficients;
☐ Large particles cause friction coefficients close to μ_0.

Results

In Table 1 the influences of the product, design and operational parameters on the most important quantities, ie the recovery, moisture content, specific throughput, conveyance, torque, power consumption and the product destruction, can be observed. The arrows indicate the particular effect on the result, when increasing the parameter. The direction of the arrow shows the tendency, its slope, the strength, eg a vertical arrow means there is a strong influence. A line simply stands for no influence and, finally an 'o' for the existence of an optimum. Of note is that this optimum again depends on the other parameters.

It is not possible, at least not in general, to name the particular dependencies in terms of general equations of the kind 'the transport torque is directly proportional to the mass throughput' because of the interactions shown in the introduction. But it should be kept in mind that all these results representing the function of a decanter can be calculated with high accuracy(4, 6, 7).

Since a change of a particular parameter improves part of the results but also worsens others, the function of a decanter centrifuge cannot be optimised without considering the specific product and the user specific demands.

Nomenclature

A	area	m^2
C	C-value: multiple of the acceleration due to gravity	—
d_h	hydraulic diameter	m
D	drag value	m
f	height of the totally saturated region in the cake	m
g	gravitational acceleration	m/s^2
G	screw pitch	m
h	product cake height	m
h_{pon}	weir height, pond surface level	m
L	geometric length	m
m	mass throughput	kg/s
M	total torque	Nm
N	normal force	N
n	speed	s^{-1}
P	power	W
R	radius	m
s	clearance	m
S	saturation	—
w	settling velocity of a particle	m/s
V	volume flow rate	m^3
x	particle diameter	m
z	axial cone co-ordinate	m

Greek symbols:

α	screw angle	—
β	cone angle	—
Γ	blade angle	—
μ	frictional coefficient	—
μ_0	dry frictional coefficient	—
μ'	frictional coefficient in Eq (8)	—
ρ	density	kg/m^3
Σ	equivalent clarification area	m^2
φ	frictional angle	—
Ω	angular speed	s^{-1}

Indices

Lower case:

acc	related to	acceleration
Br	,,	fluid bridges
c	,,	cone
cyl	,,	cylinder
d	,,	drum or bowl
diff	,,	difference between scroll and drum
l	,,	liquid
Tr	,,	conveyance
Sus	,,	suspension
s	,,	solid
[illegible]	,,	equilibrium

Uppercase:

[illegible]	,,	saturation-specific throughput

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