THE INVESTIGATION OF SEPARABILITY OF PARTICLES SMALLER THAN 5 mm BY EDDY-CURRENT SEPARATION TECHNOLOGY – PART II: NOVEL DESIGN CONCEPTS

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Separability and separation mechanisms of small particles in modern rotating type eddy-current separators (ECSs) were discussed in Part I. In order to address problems associated with this design concept, a number of novel ECSs, each with a unique design, have been developed. Part II reports on investigation into the separability and separation principles for various materials smaller than 5 mm, including fine copper wires, in three new devices: the redesigned Delft vertical ECS (VECS), prototype TNO ECS and a laboratory wet ECS (WECS). It is found that TNO ECS and WECS are more practical tools for separation of small metal particles. In particular, WECS is able to recover approximately 80% of very fine copper wires, with 0.5 mm diameter and 2 mm length. Separation principles for WECS are discussed in greater detail than other design concepts in the present study. It appears that the fledgling WECS will be most promising in the future for processing small particles. Further, aluminum separation from the –10 mm fraction of electronic scrap has been carried out using TNO ECS. It transpires that both the recovery and the grade of the aluminum concentrate are superior to those obtained with the rotary belted-drum ECS of any type.

Keywords: Vertical eddy-current separator; Wet eddy-current separator;
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1 INTRODUCTION

In Part I [1] the authors presented an analysis of the separation mechanisms of small particles in modern rotating type eddy-current separators (ECSs). It was shown experimentally that about 15–20% of 3 mm Al particles is lost to the non-conducting fraction, even if the operating conditions are optimized. This can readily be understood by analyzing the radial and tangential forces (F_r and F_t) as well as the force component (F_T) created by the electromagnetic torque (T), which are given by the authors [2]:

$$F_r = \frac{2\pi s s'^2 V B^{a2}}{\mu_0 w} \frac{(\mu_0 k \omega_{\text{drum}} \sigma R^2)^2}{1 + s'^2 (\mu_0 k \omega_{\text{drum}} \sigma R^2)^2}, \quad (1)$$

$$F_t = \frac{2\pi s s' V B^{a2}}{\mu_0 w} \frac{\mu_0 k \omega_{\text{drum}} \sigma R^2}{1 + s'^2 (\mu_0 k \omega_{\text{drum}} \sigma R^2)^2}, \quad (2)$$

$$F_T = \frac{T}{R} = \frac{s s' V B^{a2}}{\mu_0 R} \frac{\mu_0 k \omega_{\text{drum}} \sigma R^2}{1 + s'^2 (\mu_0 k \omega_{\text{drum}} \sigma R^2)^2}, \quad (3)$$

$$F_t = \left(\frac{2\pi R}{w} \right) \frac{T}{R}. \quad (4)$$

In these formulas, s is the shape factor related to the magnetization of a particle, s' is the shape factor related to the characteristic decay time of eddy currents, B^a is the amplitude of the magnetic field, k and ω_{drum} are the number of pairs of magnet poles and the angular velocity of the magnetic drum, w is the width of one pair of poles, R is the characteristic particle size, σ is the electrical conductivity, V is the volume of a particle and $\mu_0 = 4\pi \times 10^{-7}$ H/m.

As indicated by Eqs. (1)–(3), the radial eddy-current force is negligible for small particles, so that the selective separation is governed by competition between the tangential eddy-current force and the dynamic frictional force created by the electromagnetic torque. Since the dynamic frictional force is variable due to a random dynamic frictional coefficient, trajectories of small particles are unpredictable. It follows that a loss of metal particles is inevitable for the conventional rotating ECS. In an effort to address these problems, the following attempts may be

made to improve the separation selectivity of small particles:

- (1) Enhancement of the tangential eddy-current force with respect to effects of the electromagnetic torque by optimizing the magnetic drum system.
- (2) Elimination of dynamic frictional forces created by the electromagnetic torque.
- (3) Introduction of assistant separating forces, for instance, by converting negative effects of the electromagnetic torque to a positive separating effect.
- (4) Effective combinations thereof.

As is clearly indicated by Eqs. (2) and (3), the tangential eddy-current force will be enhanced by an increase of the magnetic field strength and a decrease of the magnet pole width. However, a change of the magnet pole width has no effect on the electromagnetic torque. In line with this concept is a recent design of prototype TNO ECS, which was built by The Netherlands Organization for Applied Scientific Research (TNO), Apeldoorn, The Netherlands. A number of key operating parameters involved in this new ECS is investigated in detail by using 3 mm Al, Cu and PVC particles. Also, a separability study of various binary mixtures consisting of Al/Cu and Pb/PVC was carried out in the present study. Two other devices, particularly a wet eddy-current separator (WECS), incorporating concepts 2 and 3 pointed out above, are also studied in detail by using various materials with small particle size, including fine copper wires. The separation results and principles of each separator are presented in this paper.

2 MATERIALS AND METHODS

2.1 Materials

Fine copper wires (diameter = 0.5 mm and length = 2 mm) were obtained by cutting pure copper wires with a semi-automatic cutting machine. A glass fraction ($-2.36 + 0.97$ mm) was made by first crushing clean glass material with a laboratory roll crusher and then sieving to the right fraction. Other materials, including electronic scrap, were described in Part I [1] of this paper. Furthermore, various binary mixtures were prepared for separability studies, comprising about 50% of each component by weight.

2.2 Equipment to be Used

The Delft vertical ECS (VECS) used in the present study is illustrated in Fig. 1. It consists essentially of two $1400 \times 200 \times 25$ mm iron plates,

FIGURE 1 Schematic illustration of VECS, representing its seperation principle.

FIGURE 2 Schematic presentation of the prototype TNO ECS.

each covered with 19 rows of magnets. As shown in Fig. 1, a special feeding funnel of 2000 mm height was installed in such a way as to minimize negative effects resulting from air turbulence inside the VECS. Particles leaving the funnel have an average velocity of about 6 m/s. The gap between the two iron plates is adjustable from 10 mm to infinity. However, a gap in which the field strength is about 0.6 T is desirable.

A schematic presentation of prototype TNO ECS is shown in Fig. 2. It involves a magnet system, a feeding cone, a collecting ring and a product discharge system. For reasons of secrecy, more details of this device have not yet been released.

A laboratory WECS is shown schematically in Fig. 3. Basically, it comprises a fast spinning magnetic drum, a separation tank, a product collection system and a vibratory feeder. The magnetic drum used in this study is the one from Bakker Magnetics, Model BM 29.701/18, with its details described by the authors [1]. The walls of a separation tank are made of a PMMA sheet of 5 mm in thickness. Collection bins are placed in the tank. Since PMMA is transparent, trajectories of particles to be investigated can be recorded by an image processing system.

2.3 Image Processing System

Essential components of the image processing system used in the present study consist of a CCD-camera, Model Stemmer CV-M10, and image processing software provided by Difa Measuring Systems, B.V., Breda,

FIGURE 3 Schematic of laboratory WECS.

The Netherlands. In each recording, 125 images were taken at a speed of 25 images per second.

3 EXPERIMENTAL RESULTS

3.1 Delft Vertical Eddy-Current Separators (VECSs)

After optimizing all the operating parameters of VECSs judiciously, separation of a variety of binary mixtures was carried out. The results are given in Table I. It is clear that both recovery and selectivity of 5 mm particles are far better than those of 3 mm particles. Further, Table I shows that approximately 80% of 3 mm Al particles are recovered with 80% purity, whereas only about 50% of 3 mm Cu particles, with 80% grade, are separated out. This demonstrates that the present VECS is not an effective means to separate particles smaller than 5 mm.

The present VECS was redesigned, based on the one developed by van der Valk *et al.* [3]. Owing to the fact that magnets during that time were not as powerful as they are today, the old model VECS did not find any application. A detailed modeling of the electromagnetic forces for this device is available from literature [3]. Essentially, a qualitative

TABLE I Separation results of binary mixtures by the Delft VECs

<i>Binary mixture</i>		<i>Recovery, %</i>		<i>Grade, %</i>	
Conductor	Non- or poor conductor	Al/Cu	PVC/Pb	Al/Cu	PVC/Pb
Al, 3 mm	PVC, 3 mm	78.2	83.2	81.7	79.9
Cu, 3 mm	PVC, 3 mm	47.2	81.1	83.6	42.9
Al, 5 mm	Pb, 5 mm	98.4	88.5	89.5	98.2
Cu, 5 mm	Pb, 5 mm	84.3	88.5	88.2	84.9

understanding of the separation principle for this separator can be made using a simple mathematical model, which is capable of characterizing the horizontal deflection difference between a conductor and a non-conductor ($\Delta D_{\parallel}$), as defined in Fig. 1. It holds that:

$$\Delta D_{\parallel} = \frac{1}{2} a_{\parallel} t^2 \quad (5)$$

where $a_{\parallel}$ is the horizontal acceleration created by the eddy-current forces, and t is the time period for the particle to travel through the separation channel, which can be approximated as:

$$t = H/v. \quad (6)$$

Here H and v are the height of the separation channel and the initial velocity of the particle entering the separation channel, respectively.

The magnet pole frequency (ω) observed by the moving particle can be written as:

$$\omega = \frac{2\pi k}{t} \quad (7)$$

where k is the number of pairs of magnet poles.

We have a relationship [1]:

$$a_{\parallel} \propto \omega B_0^2 \quad (8)$$

where B_0 is the amplitude of the magnetic field halfway between two plates. Therefore, we obtain that:

$$\begin{aligned} \Delta D_{\parallel} &\propto \omega B_0^2 t^2 \\ &\propto 2\pi k B_0^2 \frac{H}{v}. \end{aligned} \quad (9)$$

Equation (9) suggests that the deflection difference and hence the separation selectivity of small particles shall be enhanced substantially with the increase of k and B_0 . This can be realized by improving

configuration of the magnet system. Besides, as indicated by Eq. (9), increase of the height of the separation channel is expected to improve the selectivity.

When compared to the rotating type ECS [1], the electromagnetic torque on small particles moving through the separation channel of VECS is reduced, due to the fact that two electromagnetic torques resulting from two rows of magnets counteract each other. It is true, though, that the two electromagnetic torques will not be counteracted completely if collisions between the particles and the internal walls of the two plates take place. It is therefore recommended that the particles to be separated be fed in the middle of the separation channel.

3.2 TNO Eddy-Current Separators (TNO ECSs)

As the first step in the assessment of the potential of TNO ECSs, a number of important operating parameters was studied. Figure 4 shows

FIGURE 4 Materials recovery as a function of rotation speed of the magnet system (particle size = 3 mm, ring diameter = 245 mm, ring height = 27 mm angle of feeding cone = 30°).

the recovery of various 3 mm materials as a function of the rotation speed of the magnet system. Clearly, the recovery of metal particles increases with the rotation speed of the magnet system (MS), whereas the recovery of non-metal PVC particles is independent of the rotation speed of MS, as might be expected. It was found, however, that about 20% of PVC by weight reports to the conducting fraction. One reason is that the feeding cone presents such an inclined surface to the particles that it is easy for PVC particles to flip over to the collecting ring. The small inner diameter of the collecting ring also promotes a jumpover of PVC particles to the conducting fraction.

Figure 5 shows the recovery of 3 mm Al and PVC as a function of the rotation speed of MS by using a large collecting ring. It is found that the recovery of metal particles is much lower using a large ring than using a small ring. However, the product purity is improved, since only about 3% of PVC particles report to the conducting fraction. In addition, it appears in Fig. 5 that if a flatter cone is used, i.e. one with a smaller angle, fewer PVC particles jump into the conducting fraction.

FIGURE 5 Materials recovery as a function of rotation speed of the magnet system (particle size = 3 mm, ring diameter = 290 mm, ring height = 2 mm).

After a careful study of the key parameters of TNO ECSs, the separation of a variety of binary mixtures was conducted. The results are presented in Fig. 6, showing that a selective separation of both 3 and 5 mm particles can easily be made by adjusting the height of the collecting rings. It is seen that both recovery and grade of 3 mm Al particles are in excess of 90%. In a third series of experiments, the separation of Al from electronic scrap was performed after optimization of the operating conditions (Table II). About 96% of Al particles were recovered, while maintaining 70% purity in a single pass. The main contaminants in the Al product are plastics particles with copper laminates. In the light of both the recovery and grade of Al products, TNO ECS is superior to the rotating type ECS that was detailed by the authors in Part I [1].

FIGURE 6 Separation results of binary mixtures using TNO ECS (rotation speed of the magnet system = 3000 rpm, ring diameter = 245 mm, angle of the feeding cone = 15°).

TABLE II Separation results of electronic scrap using TNO ECS (single pass)

	<i>Weight, %</i>	<i>Al grade, %</i>	<i>Al recovery, %</i>
Concentrate	6.5	67.2	95.8
Waste	93.5	0.2	4.2
Total	100.0	4.5	100.0

Equations (1)–(3) are valid for TNO ECS, as well as for the rotary belted-drum ECS. Since the details of the TNO device are kept confidential, only a qualitative evaluation is given here. The MS of the separator consists of 26 magnet poles, i.e. 13 pairs of poles. The width (w_{TNO}) of one pair of magnet poles is about $w_{\text{TNO}} = 40$ mm, whereas the width (w_{rot}) in a 24-pole belted-drum ECS is typically $w_{\text{rot}} = 80$ mm. This means that the width of one pair of the magnet poles in TNO ECS is about half of that in the conventional rotary ECS. In addition, the gap between the MS and the feed stream in TNO ECS is reduced to a few millimeters, so that the amplitude of the field is increased to about 0.5 T. Typically, the effective field strength of the rotary belted-drum ECS is about 0.3 T. According to Eq. (2), the ratio of the tangential eddy-current forces generated by the two ECSs can be evaluated as:

$$\begin{aligned} \frac{F_t^{\text{TNO}}}{F_t^{\text{rot}}} &\approx \left(\frac{B_{\text{TNO}}}{B_{\text{rot}}} \right)^2 \left(\frac{w_{\text{rot}}}{w_{\text{TNO}}} \right) \\ &\approx \left(\frac{0.5}{0.3} \right)^2 \left(\frac{80}{40} \right) \approx 6. \end{aligned} \quad (10)$$

Equation (10) indicates that the tangential eddy-current force of TNO ECS (F_t^{TNO}), acting on a given small metal particle, is approximately six times that of the rotary belted-drum ECS (F_t^{rot}). As a consequence, the dominant separating force, i.e. the tangential force, is enhanced considerably, with respect to the effects of the electromagnetic torque.

Further, negative effects of the electromagnetic torque on small particles in the rotary ECS are converted to a positive separating effect in TNO ECS. Unlike the separation on a belted-drum ECS, both the tangential force and the torque-derived frictional force act at right angle with respect to the feed velocity. This means that the particles tend to be separated out, regardless of whether the tangential force dominates the torque-derived force or vice versa. Accordingly, there is no doubt that a combination of those improvements leads to a better separation of small particles.

3.3 Wet Eddy Current Separators (WECSs)

Research and development of ECSs for small particles has so far been orientated towards a dry process. In this paper, the authors present a laboratory WECS, illustrated in Fig. 3. The present WECS, which is far from ideal, is used mainly to verify our concepts.

Figure 7 shows materials recovery as a function of the rotation speed of the magnetic drum. It is demonstrated that the recovery of both Cu and Al particles increases rapidly as the drum speed increases. With the drum speed exceeding 30 rps, i.e. 1500 rpm, the recovery of metal particles approaches 100% whilst the recovery of non-metal glass particles remains less than 5%. This implies that it is easy to obtain a selective separation of small metal particles from non-metal particles.

Two binary mixtures consisting of 3 mm Al or Cu and glass particles were investigated. The separation results are given in Fig. 8. It is shown

FIGURE 7 Materials recovery as a function of drum speed for the WECS.

FIGURE 8 Separation results of binary mixtures using the WECS.

that high quality Al and Cu products with the grade greater than 98% are attained, while maintaining approximately 97% and 100% recovery, respectively. It appears that WECS is the best of all the design concepts studied so far, when aiming at selectively separating small particles. A further investigation of the separation of fine copper wires (diameter = 0.5 mm and length = 2 mm), that cannot be realized by any dry ECS, shows again a great potential and promise of WECS. Figure 9 indicates that more than 80% of copper wires are recovered by WECS at 50 rps drum speed. However, if the magnetic drum is stationary, i.e. at 0 rps, less than 3% copper wires report to the conducting fraction, implying that hydrodynamic effects of the particle shape can be eliminated as a driving force for the separation.

Trajectories of particles in WECS can also be simulated by our ECSIM software [2,4]. At this point, the fluid dynamics forces must be emphasized, in addition to the eddy-current forces involved in the

FIGURE 9 Materials recovery using WECS for copper wires. Case I: Fine copper wires with diameter $d=0.5$ mm and length = 2.0 mm; drum speed = 50 rps. Case II: Fine copper wires with diameter $d=0.5$ mm and length = 2.0 mm; drum speed = 0 rps. Case III: Glass particles of $-2.36 + 0.97$ mm; drum speed = 50 rps.

separation system. On the basis of a dimensional analysis, two linear drag and lift forces ($\mathbf{F}_{\text{drag}}$ and $\mathbf{F}_{\text{lift}}$) as well as the drag torque ($\mathbf{T}_{\text{drag}}$) can be approximated as (the bold letters denote a vector identity):

$$\mathbf{F}_{\text{drag}} = -K_{\text{drag}} \frac{\rho_f |\mathbf{v}| \mathbf{v}}{2}, \quad (11)$$

$$\mathbf{F}_{\text{lift}} = K_{\text{lift}} \rho_f \boldsymbol{\Omega} \times \mathbf{v}, \quad (12)$$

$$\mathbf{T}_{\text{drag}} = -K_{\text{torque}} \rho_f |\boldsymbol{\Omega}| \boldsymbol{\Omega}. \quad (13)$$

Here K_{drag} , K_{lift} and K_{torque} are coefficients depending on the size and shape of a particle as well as its orientation with respect to $\boldsymbol{\Omega}$, the angular velocity of the particle (assuming that $\boldsymbol{\Omega}$ is always perpendicular to $\mathbf{v}$, i.e. the linear velocity of the particle), and ρ_f is the fluid density.

For bodies of revolution, such as spheres, disks and cylinders, the orientation is defined by the axis of revolution $\mathbf{e}_\zeta$. A practical approach for particles of these shapes is to consider only two extreme possibilities $\Omega \parallel \mathbf{e}_\zeta$ and $\Omega \perp \mathbf{e}_\zeta$, with coefficients K_1 and K_2 , respectively, and interpolate for orientations between the extremes:

$$K = \frac{\Omega_\zeta^2 K_1 + (\Omega^2 - \Omega_\zeta^2) K_2}{\Omega^2}. \quad (14)$$

The estimated values of coefficients K_1 and K_2 for spheres, disks and cylinders can be found in the literature or measured by independent experiments [5]. In the case of spheres, $K_{1,\text{drag}}$ and $K_{2,\text{drag}}$ are known to be $0.44\pi R^2$ in the turbulent limit.

As indicated by Eqs. (11)–(13), linear forces and the torque are proportional to the fluid density. It may therefore be anticipated that the lift force can be enhanced considerably if separation occurs in water instead of in air. By combining the electromagnetic torque with equations of fluid dynamics, we obtain a quantitative separation criterion, i.e. a separability factor denoted by R_{sf} , which is in effect the ratio of the lift force to the force resulting from the gravitational and buoyant forces:

$$R_{\text{sf}} = \frac{F_{\text{lift}}}{(\rho - \rho_f)Vg} \approx 0.087 B^a \sqrt{\frac{\omega \sigma R}{\rho - \rho_f}}. \quad (15)$$

For instance, for a 18-pole magnetic drum spinning at 50 rps, the separability factor for 3 mm Cu particles at a position where the field strength is 0.05 T will be about 0.75. This means that the particles will be deflected away about at an angle of 30° from the vertical. This result is validated both by detailed simulations and by experiments.

Figure 10 shows simulated trajectories of 3 mm Al, Cu and glass particles, under the conditions similar to the experiments. It is clear that copper particles are deflected away by the lift forces at an angle of about 30° from the vertical, whereas the glass particles just settle down due to the gravitational force, buoyant force and drag force. In order to substantiate the simulation results, particle trajectories were also recorded by the image processing system. Figures 11 and 12 show the recorded trajectories of glass and copper particles of 3 mm, respectively. It is seen

FIGURE 10 Simulated trajectories of glass, Al and Cu particles of 3 mm (Trajectory 1: Al; Trajectory 2: Cu; Trajectory 3: Glass).

that glass particles settle down and 3 mm Cu particles are deflected about 200 mm away, on average, with respect to the center of the magnetic drum. Once again, the deflection angle of 3 mm Cu particles with respect to the vertical is about 30°, as argued above. When compared to Fig. 10, experimental results are in a very good agreement with the simulated ones. We conclude that the wet eddy current separation technology is the most promising approach to a selective separation of small particles.

4 DISCUSSION

4.1 Critical Trade-Offs of Different ECSs with Various Concepts for Small Particles

We have so far investigated ECSs with four basic design concepts for separating small metal particles, which encompass the rotating drum

FIGURE 11 Trajectories of glass particles captured by an image processing system.

type ECS, VECS, TNO ECS and WECS. Their separation performance is compared and evaluated throughout this paper series. In general, the finer is the particle size, the more costly will be ECS. In comparison to dry ECS, WECS will incorporate more complicated mechanical components. Furthermore, products obtained by WECS need a dewatering system. Therefore, WECS will be an expensive approach for small particles. Nevertheless, selective separation of different metals in one step in WECS might offset the processing cost.

FIGURE 12 Trajectories of 3 mm Cu particles captured by an image processing system.

Critical comparison of the four concepts is given in Table III. It seems that the dry rotating drum type ECS will still play a key role in separating small particles. However, in terms of performance, WECS is the best concept in this context. The authors maintain that in the future it will become one of the key practical concepts in the recycling industry for handling waste streams containing small metal particles smaller than 5 mm in diameter.

TABLE III Critical comparison of ECS with various design concepts for small particles

<i>Design concept</i>	<i>Throughput</i>	<i>Separation selectivity</i>	<i>Operating difficulty (sensitivity to the magnetics)</i>	<i>Maintenance</i>	<i>Number of non-ferrous products in one step</i>	<i>Investment cost for 1 ton/h</i>	<i>Final results</i>
Dry							
Rotating drum type	++	+	0	0	0	0	+++
VECS	0	0	-	+	0	-	-
TNO ECS	+	++	-	-	0	+	++
Wet							
Rotating drum WECS	+	+++	+	-	+	-	++++

Note that "0", "+", "-" and "++" denote base, negative and positive respectively.

4.2 Perspectives of ECS for Small Particles

The market of processing waste streams containing small metal particles is expected to grow substantially in the near future, as a result of (1) continuing arisings of diversified waste streams like the end-of-life electric and electronic equipment; (2) growing environmental awareness; (3) more stringent legislation; and (4) more costly landfilling of metal-containing wastes. For instance, +10 mm fraction of the ash residue from municipal solid waste incinerators is currently processed to extract metal values. The finer fraction is, however, landfilled since there is no practicable and cost-effective technology yet available. It is estimated that this fraction amounts approximately to 300,000 tons annually in The Netherlands alone. We predict that an economically and technically viable separation technology to recover small metal particles from waste will be in great demand in the near future.

5 CONCLUSIONS

It is concluded, based on the present study, that small metal particles smaller than 5 mm can be separated effectively through eddy-current separation technology, by increasing the residence time of the particles in the effective separation zone, by enhancing the tangential eddy-current forces and at the same time eliminating negative effects of the electromagnetic torque or converting them to an assistant separating effect, and by performing separation in water instead of in air. Particularly, WECS, in which the electromagnetic torque is converted to a dominant separating force, needs to be developed further with a view towards a selective separation of small particles.

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References

- [1] S. Zhang, P. Rem and E. Forssberg, The investigation of separability of particles smaller than 5 mm by eddy current separation technology – Part I: rotating type eddy current separators. *Magnetic and Electrical Separation* **9** (1999) 233.
- [2] S. Zhang, P. Rem and E. Forssberg, Particle Trajectory simulation of two-drum eddy current separators. *Resources, Conservation & Recycling* **26** (1999) 71–90.
- [3] H. Van der Valk, B. Braam and W. Dalmijn, Eddy current separation by permanent magnets Part I: Theory. *Resource and Conservation*, **12** (1986) 233–252.
- [4] P. Rem, E. Beunder and A. van der Akker, Simulation of eddy-current separators. *IEEE Trans. Magn.* **34** (1998) 2280–2286.
- [5] D. Bongers, Eddy current separation of – 10 mm particles. Report No. TA GK 97.03, Department of Raw Materials Technology, Delft University of Technology, 2628 RX Delft, The Netherlands (1997).