Gravity Separation of Particulate Solids in Turbulent Fluid Flow

Jürgen Tomas
Otto-von-Guericke-University Magdeburg, Mechanical Process Engineering, P.O.Box 4120, D - 39106 Magdeburg, phone: +49 391 67 18783, fax: +49 391 67 11160,
e-mail: juergen.tomas@vst.uni-magdeburg.de

Abstract
The liberation of building rubble by comminution produces a predominantly mineral mixture with a density distribution of $\rho_s = 1.8 - 2.7 \text{ g/cm}^3$. As a result of the relatively narrow density range, the requirements regarding the sharpness of the process employed for the separation of partially liberated aggregate and concrete-brick rubble are very high. For the gravity separation a test rig was built consisting of zigzag channel, fan, air cyclone, filter and particle feeding system. Specific mass flow rates 3 to 16 t/(m$^2\cdot$h) related to apparatus cross-sectional area and mass related energy consumption 0.2 to 8 kWh/t were obtained. To assess the efficiency, the separation function is determined and compared with a theoretical model of multistage turbulent cross-flow separation. On the basis of the well-known separation sharpness as well as geometrical variability of a zigzag apparatus, it could be shown that this separation principle is well suited for the gravity separation of mineral materials.

Keywords: Cross-flow gravity separation model, separation efficiency, building rubble recycling

1 Introduction
The liberation of building rubble by comminution produces a predominantly mineral mixture with a density distribution of $\rho_s = 1.8 - 2.7 \text{ g/cm}^3$ [32]. As a result of the relatively narrow density range, the requirements regarding the sharpness of the process employed for the separation of partially liberated aggregate and concrete-brick rubble are very high.

Table 1: Selected separation processes for the recycling of building and domestic waste

<table>
<thead>
<tr>
<th>Wet separation</th>
<th>Dry separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Float and sink cleaning [36], [29]</td>
<td>• Classification [7]</td>
</tr>
<tr>
<td>• Upward flow [12]</td>
<td>• Hand sorting [9]</td>
</tr>
<tr>
<td>• Jig [4], [13]</td>
<td>• Automatic sorting [27]</td>
</tr>
<tr>
<td>• Washing drum [10]</td>
<td>• Counter-, cross-flow aeroseparation [22]</td>
</tr>
<tr>
<td></td>
<td>• Pneumatic table [8]</td>
</tr>
<tr>
<td></td>
<td>• Sloping separating belt [27]</td>
</tr>
<tr>
<td></td>
<td>• Slinger [9]</td>
</tr>
<tr>
<td></td>
<td>• Eddy current separator [26]</td>
</tr>
</tbody>
</table>

The separation processes currently employed in the recycling of building materials remove mainly the lightweight impurities such as paper, wood, films, insulating materials and pieces of plastic ($\rho_s = 0.1 - 1.2 \text{ g/cm}^3$) by wet or dry separation. In such cases, the range of unsharpness of the cutpoint can be defined in the intermediate range ($\rho_s = 1.2 – 1.8 \text{ g/cm}^3$), so that equipment with relatively low separation efficiency is still adequate for these applications. Table 1 provides an overview of the state-of-the-art in respect of separation for recycling building materials [1], [5], [9], [13], [14], [22], [36].
Wet and dry separation have different advantages and disadvantages. Dry separation is more cost-effective in terms of its energy requirement as problems regarding the treatment of process water and its disposal do need to be considered, and is especially suitable for mobile and semi-mobile processing plants. Wet separation is useful for the removal of pollutants from contaminated building waste [12].

For the separation of building rubble, mainly classifiers are used in practice. The upward flow or single-stage cross-flow separators commonly employed for dry separation in an air flow separate the material feed according to the respective settling velocities of the different components. The separation behaviour is influenced decisively by the particle size, particle shape and particle density of the components to be separated. An air classifier can separate the material according to one of these parameters providing the influence of the other two variables is minimised.

The separation of totally or partially liberated aggregate particles in the size range from \(d = 2 - 16\) mm therefore presents a challenge to the separation sharpness and the efficiency of the equipment. Tests were carried out in a zigzag channel to establish whether the high separation sharpness required can be achieved in a multistage turbulent cross-flow separation apparatus.

### 2 Fundamentals of the Aeroseparation of Building Rubble

The basis for studying a separation process in a fluid cross-flow is the balance of the forces of buoyancy, weight and fluid resistance of a particle. With this balance, it is possible to obtain a correlation between particle size and the quasi-stationary settling velocity \(v_s\) in the field of gravity \(g\):

\[
v_s = \frac{2}{c_w} \cdot \rho_s - \rho_f \cdot \frac{V_p}{A_p} \cdot \frac{V_p}{A_p} \cdot g\]

Here \(A_p\) is the side-fed cross-sectional area, \(c_w\) the drag coefficient of the fluid flow pattern around the particles, \(V_p\) the particle volume and \(\rho_f\) the fluid density. The density of the solid particles \(\rho_s\) depends on the inner porosity (up to 95 % for insulating materials) and pore saturation with a liquid.

In the separation of particles of varying density \(\rho_s\) the principle of what is termed “equivalent falling classes” [25], i.e. classes with equal settling velocity, can be formulated as follows. If the particle shape is constant, “large” and “lightweight” particles settle just as fast as “small” and “heavy” particles. With \(d_i\) to \(d_{i+1}\) as the particle size of the class \(i\) to \(i+1\) as well as \(\rho_{s,S}\) and \(\rho_{s,L}\) as the particle densities of the heavy fraction (index S) and the lightweight fraction (index L), the following applies:

\[
v_s(d_{i+1}, \rho_{s,L}) = v_s(d_i, \rho_{s,S})
\]

Depending on the particle flow patterns \(v_s \propto d^{\alpha}\) [24] and with the relationship \(c_w \propto Re^{\frac{1-2\alpha}{3}}\) (particle Reynolds number \(Re = \frac{v_s \cdot d \cdot \rho_f / \eta_f}{\rho_f}\)), it then follows, Table 2:

<table>
<thead>
<tr>
<th>Exponent (\alpha)</th>
<th>(\frac{\alpha+1}{3-\alpha})</th>
<th>Flow pattern</th>
<th>Reynolds number</th>
<th>Drag coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1/2</td>
<td>laminar (Stokes)</td>
<td>(Re &lt; 1)</td>
<td>(c_w \propto Re^{-1})</td>
</tr>
<tr>
<td>(2 &lt; \alpha &lt; 1/2)</td>
<td>1/2 ... 1</td>
<td>transition</td>
<td>(1 &lt; Re &lt; 10^3)</td>
<td>(c_w \propto Re^{1-2\alpha})</td>
</tr>
<tr>
<td>1/2</td>
<td>1</td>
<td>turbulent (Newton)</td>
<td>(10^3 &lt; Re &lt; (2 - 4) \times 10^5)</td>
<td>(c_w \propto Re^{0})</td>
</tr>
</tbody>
</table>

Table 2: Equivalent-falling condition dependent on the particle flow-around pattern.
\[
\frac{d_{i+1}}{d_i} = \left( \frac{\rho_{s,S} - \rho_f}{\rho_{s,L} - \rho_f} \right)^{\frac{\alpha+1}{3\alpha}} \quad \text{or} \quad \frac{v_s}{v_{sT}} = \left( \frac{d}{d_T} \right)^{\frac{\alpha}{3}} = \left( \frac{\rho_s - \rho_f}{\rho_{s,T} - \rho_f} \right)^{\frac{\alpha+1}{3}}
\] (3)
Table 3: Separators with turbulent fluid flow [24], re-calculated from separation results

<table>
<thead>
<tr>
<th>Cross-flow separation apparatus</th>
<th>Apparatus Reynolds no. $Re = \frac{u \cdot D}{\nu}$</th>
<th>Degree of turbulence $Tu = \sqrt{\frac{u''^2}{u}}$</th>
<th>Turbulent diffusion coefficient in $(cm)^2/s$ $D_t = A \cdot \sqrt{u''^2}$</th>
<th>Bodenstein number $Bo_s = \frac{\nu \cdot L}{D_{ts}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screw classifier</td>
<td>$n_s \cdot \frac{D_s^2}{\nu}$</td>
<td>0.05 – 0.15</td>
<td>$0.014 \cdot n_s \cdot \frac{D_s^2}{B} + \frac{0.48 \cdot \Psi}{B}$</td>
<td>$n_s \cdot \frac{D_s^2}{D_t} \approx 100$</td>
</tr>
<tr>
<td></td>
<td>$Re_{crit} \approx 10^4$</td>
<td></td>
<td>$5 - 50$ or $\approx (2)^2 - (7)^2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^4 - 5 \cdot 10^5$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rake classifier</td>
<td>$n_R \cdot \frac{L_R^2}{\nu}$</td>
<td></td>
<td>$0.31 \cdot n_R \cdot \frac{L_R^2}{B} + \frac{0.48 \cdot \Psi}{B}$</td>
<td>$n_R \cdot \frac{L_R^2}{D_t} \approx 1.5 - 3$</td>
</tr>
<tr>
<td></td>
<td>$10^4 - 5 \cdot 10^5$</td>
<td></td>
<td>$30 - 100$ or $\approx (5,5)^2 - (10)^2$</td>
<td></td>
</tr>
<tr>
<td>1.3 Cyclones</td>
<td>$\frac{u \cdot D_C}{\nu}$</td>
<td>0.01 – 0.05</td>
<td>$8 \cdot 10^{-4} \cdot u \cdot D_C$</td>
<td>$u \cdot \frac{D_C}{D_t} \approx 10^3$</td>
</tr>
<tr>
<td></td>
<td>$Re_{crit} \approx 10^3$</td>
<td>$\approx 0.1$ at input</td>
<td>$0.0035 \cdot u \cdot D_C$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$10^5 - 10^6$</td>
<td></td>
<td>$1 - 20$ or $\approx (1)^2 - (4,5)^2$</td>
<td></td>
</tr>
<tr>
<td>1.4 Zigzag separator $^1)$</td>
<td>$\frac{u \cdot b}{\nu}$</td>
<td>$Tu \approx \frac{D_t}{u \cdot b} \approx 0.11 - 0.13$</td>
<td>$(0.11 - 0.13) \cdot u \cdot b$</td>
<td>$\frac{u \cdot b}{D_t} \approx 1 - 15$</td>
</tr>
<tr>
<td></td>
<td>$10^4 - 6 \cdot 10^5$</td>
<td></td>
<td>$2000 - 4000$ or $\approx (45)^2 - (63)^2$</td>
<td></td>
</tr>
<tr>
<td>2. Counter-flow classifier</td>
<td>$\frac{u \cdot D}{\nu}$</td>
<td></td>
<td>$0.02 \cdot u \cdot D$</td>
<td>$0.5 - 50$</td>
</tr>
<tr>
<td></td>
<td>$10^3 - 10^6$</td>
<td></td>
<td>$200 - 2000$ or $\approx (14)^2 - (45)^2$</td>
<td></td>
</tr>
</tbody>
</table>

As the models of counter-current separations drawn up so far [6], [3] have proven unsuitable or too complex [30] for the evaluation of the multistage cross-flow gravity separation studied here, in order to describe the process efficiency, the separation tapping model of a turbulent cross-flow hydro-
classification developed by Schubert [23] and Neeße [16] was supplemented with a model for multistage turbulent cross-flow aeroseparation [34]. Provided that the particle and fluid flow characteristics are more or less equivalent [18], [24], 27 the effective dimensionless turbulence variables can be calculated from the separation results described in the following, namely the averaged channel Reynolds number \( Re = u \cdot b / \nu \approx 10^4 \cdot 6 \cdot 10^5 \) and degree of turbulence \( Tu \approx 0.11 - 0.13 \), Table 3. Because of the comparable high degree of turbulence in the zigzag channel the turbulent particle diffusion or eddy diffusion coefficient of fluid \( D_{t,s} \approx D_t \approx (45 \text{ cm})^2 / \text{s} - (63 \text{ cm})^2 / \text{s} \) measures also high. Additionally, the amounts in brackets can be physically correct interpreted as the local particle position shift squared, averaged and related to a time increment, i.e. 2\(^{nd}\) statistical momentum of particle concentration distribution, see Einstein or Fokker-Planck-Equation [19]. Consequently, the ratio of convective to diffusive particle transport expressed by means of the Bodenstein number \( Bo_s \approx Bo = u \cdot b / D_t \approx 1 – 15 \) is comparably small.

Solving the Fokker-Planck-Equation for one-dimensional steady-state particle transport an algebraic formulation of particle number concentration distribution in a process chamber is found [15]. Balancing now the particle flow in the zigzag channel and taking into account the turbulent particle flow-around pattern in the z\(_L\) overflow separation stages or z\(_S\) in the underflow, resp., the normalised separation function results as follows (\( \dot{V}_L, \dot{V}_S \) total volume flow rates of lightweight and heavy particles) [35]:

\[
T_{zL,zS}\left(\frac{\rho_{s,j} - \rho_f}{\rho_{s,T} - \rho_f}\right)_{d=\text{const.}} = \frac{1}{1 + \left(\frac{\dot{V}_L}{\dot{V}_S}\right)^{\rho_{s,j} - \rho_f}}
\]

This fractional grade function Eq.(4) corresponds to a probability distribution of a class j of the measurable density of the porous particles \( \rho_{s,j} \) (the pore space in hardened cement paste measures around 20 ... 30 \%) being discharged in the heavy fraction S. In his case, the cut-point (average separation density) is defined with \( T_{zL,zS}(\rho_{s,T}) = 0.5 \) probability. For equal fractional grade efficiencies of the z\(_L\) lightweight fraction separation stages and z\(_S\) heavy fraction separation stages, the component mass balance returns the total separation probability (feed index A, [35]):

\[
T_{\text{tot},j} = R_{m,S} \cdot \frac{q_S(\rho_s)}{q_A(\rho_s)} = \frac{1}{1 + (1 - T_{zL,j})^{\rho_s}}
\]

For a symmetrical separation with the same number of stages in the lightweight and heavy particle flow (\( z_L = z_S = z \)), the total separation function can be simplified with Eqs.(4) and (5) to [35]:

\[
T_{\text{tot},j} = \frac{1}{1 + \left(\frac{\dot{V}_L}{\dot{V}_S}\right)^{\rho_{s,j} - \rho_f}}
\]

Hence, the slope of the separation function can be characterised by an elegant analytical formulation of the overall separation sharpness:

\[
\kappa_{\text{tot}} = \frac{\rho_{s,25}}{\rho_{s,75}} = \left[ \frac{z \cdot \ln\left(\frac{\dot{V}_L}{\dot{V}_S}\right) - \ln 3}{z \cdot \ln\left(\frac{\dot{V}_L}{\dot{V}_S}\right) + \ln 3} \right]^2 \leq 1
\]

Separation in the turbulent particle flow pattern can only be achieved with appropriate separation sharpness if the separator has a comparably high number of separation stages and if a sufficiently
high ratio between the lightweight and heavy material volume flow rates $V_L / V_S$ can be maintained. This is commensurate with practical experience gained with classification, see Kaiser [11]. Because of this fact, the multistage separation model is to be generalised for a wide range of flow pattern concerning the characteristic particle settling velocity, Table 4.

With the effective total number of separation stages $n_e$ (the feed separation stage both in the overflow and the underflow is included in this number),

$$n_e = 2 \cdot z_e - 1 \quad \text{(8)}$$

an additional degree of freedom $z = z_e$ is obtained, which, on the one hand, can be used to fit the measured values to a physically valid separation function Eq. (6) especially with regard to their S-shape. On the other hand, the so-called separation stage utilisation coefficient represents an additional parameter to assess separation efficiency in case of small density differences.

$$\eta_T = n_e / n \quad \text{(9)}$$

Table 4: Assessment characteristics for multistage cross-flow separation in a symmetrical apparatus with $z_o = z_u = z$

<table>
<thead>
<tr>
<th>Separation function $T_{tot}(\xi / \xi_T) =$</th>
<th>Cut characteristic $\xi_T = \xi_{50}(T_{tot} = 0.5) =$</th>
<th>Separation sharpness $\kappa_{tot} = \xi_{25} / \xi_{75} =$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluid flow separation $\xi = v_s$</td>
<td>$v_s = \sqrt{2 \cdot (\rho_{st} - \rho_f) \cdot \frac{V_p \cdot g}{c_w \cdot \rho_f \cdot A_p}}$</td>
<td>$z \cdot \ln \left( \frac{\xi_o}{\xi_u} \right) - \ln 3$</td>
</tr>
<tr>
<td>$1 + \left( \frac{\xi}{\xi_f} \right)^{\frac{1}{1 - \frac{d}{d_f}}} z$</td>
<td>$z \cdot \ln \left( \frac{\xi_o}{\xi_u} \right) + \ln 3$</td>
<td>$z \cdot \ln \left( \frac{\xi_o}{\xi_u} \right) + \ln 3$</td>
</tr>
<tr>
<td>Classification $\xi = d$</td>
<td>$d_T \approx \frac{\rho_f}{3 \cdot c_w \cdot g} \left[ \frac{D_{ls} \cdot \ln \left( \frac{\xi_f}{\xi_G} \right)}{h} \right]^2$</td>
<td>$z \cdot \ln \left( \frac{\xi_o}{\xi_u} \right) - \ln 3$</td>
</tr>
<tr>
<td>$\rho_{st} \approx \frac{\rho_f}{3 \cdot c_w \cdot g} \left[ \frac{D_{ls} \cdot \ln \left( \frac{\xi_f}{\xi_S} \right)}{h} \right]^2$</td>
<td>$z \cdot \ln \left( \frac{\xi_o}{\xi_u} \right) + \ln 3$</td>
<td>$z \cdot \ln \left( \frac{\xi_o}{\xi_u} \right) + \ln 3$</td>
</tr>
<tr>
<td>Gravity separation $\xi = \rho_s$</td>
<td>$d_T \approx \frac{\rho_f}{3 \cdot c_w \cdot g} \left[ \frac{D_{ls} \cdot \ln \left( \frac{\xi_f}{\xi_G} \right)}{h} \right]^2$</td>
<td>$z \cdot \ln \left( \frac{\xi_o}{\xi_u} \right) - \ln 3$</td>
</tr>
<tr>
<td>$\rho_{st} \approx \frac{\rho_f}{3 \cdot c_w \cdot g} \left[ \frac{D_{ls} \cdot \ln \left( \frac{\xi_f}{\xi_S} \right)}{h} \right]^2$</td>
<td>$z \cdot \ln \left( \frac{\xi_o}{\xi_u} \right) + \ln 3$</td>
<td>$z \cdot \ln \left( \frac{\xi_o}{\xi_u} \right) + \ln 3$</td>
</tr>
</tbody>
</table>

Table 4: Assessment characteristics for multistage cross-flow separation in a symmetrical apparatus with $z_o = z_u = z$

number of separation stages and $\alpha$ see Table 2

<table>
<thead>
<tr>
<th>Fluid flow separation</th>
<th>Classification</th>
<th>Gravity separation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\xi = v_s$</td>
<td>$\xi = d$</td>
<td>$\xi = \rho_s$</td>
</tr>
</tbody>
</table>

$\xi_o$, $\xi_f$, $\xi_S$ overflow, fine or lightweight particle suspension volume flow rates

$\xi_u$, $\xi_G$, $\xi_S$ underflow, coarse or heavy particle suspension volume flow rates

$\alpha = 2$ laminar (Stokes), $\alpha = 0.5$ turbulent (Newton) flow pattern acc. to $v_s \propto d^\alpha$ [24]

### 3 Set-up of the Test Rig

For the separation of mineral materials, a test rig, consisting of a zigzag channel measuring $173 \times 200 \text{ mm}^2$, a feed unit, a fan, a cyclone and cloth filter, was set up, Figure 1.

The separation process can be observed through the glass side walls of the channel. The mass flow rates of the feed materials and the separation products are determined by means of weight cells. In addition, during the tests, the air volume flow rate, the average channel velocity, the pressure drop versus the zigzag apparatus, the pressure drop versus the filter and the temperature and relative humidity at significant points can be measured, Figure 2 (5 1996).
Zigzag classifiers are usually classed as counter-current classifiers [3]. The separation process in the zigzag channel can, however, also be understood as a series arrangement of cross-flow separation stages [25]. In each stage, so-called vortex rolls are formed, to which one fractional grade can be assigned respectively in the ideal case [30].

Figure 1: Setup of the test rig

Figure 2: PI-flow chart of the test rig

Usually the feed material is added to the separation process at the centre – relative to the number of stages in the zigzag channel. In each stage of the apparatus, separation into a lightweight and heavy fraction takes place. The heavy particles slide down the downwards sloping channel walls and the lightweight particles are swept up with the air flow at the two upwards sloping channel walls. At the bends of the zigzag channel, these two currents cross the channel so that a cross-flow separation takes place. The good separation characteristics of a zigzag separator are based on the series arrangement of several such stages [11], [30], [6], [3], [5], [31], [33].
4 Assessing the Separation Model for Air Classification

As part of preliminary studies, the separation model in Eq. (6) was applied for the classification of sand/split and gravel, Table 5. In Figure 3, the measured values for the three separation experiments with the cut particle size \( d_T = 2.1; 4.6 \) and \( 6.6 \) mm are shown. Despite reduction by particle shape impact, the quasi-stationary settling velocity of spheres \( \nu_{sT} \) at this cut point is higher than the averaged channel air flow rate \( u \) being characteristically for the predominant cross-flow separation principle.

For the purpose of comparison, the corresponding model curves with fitted, i.e. effective, stage numbers \( z_L = z_S = z_e = 1.4, 1.1 \) and 1.1 are also plotted. With this additional degree of freedom \( z \), the experimental separation processes with the S-shaped curves typical of air classification \( (\rho_s = \text{const.}) \) can be reproduced very well. From these, separation efficiencies of \( \kappa = 0.7 \) - 0.75 can be read, which can be considered as good (range \( \kappa = 0.6 - 0.8 \) [21]). However, for this classification, effective stage number in the range \( n_e = 1.2 - 1.8 \) results.

This means that the seven separation stages of the apparatus are only utilised to a satisfactory extent at \( \eta_T = n_e/n = 17\% - 26\% \). Remarkable in technical terms are also the mass flow rates of 3 - 8.5

Table 5: Comparison of classification results with the separation model according to Eq. (6)

<table>
<thead>
<tr>
<th>according to Figure 3</th>
<th>∆ sand/split</th>
<th>● split</th>
<th>♦ split/gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>channel velocity ( u ) in m/s</td>
<td>7.5</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>air volume flow rate ( \nu_{gT} ) in m³/s</td>
<td>0.3</td>
<td>0.32</td>
<td>0.38</td>
</tr>
<tr>
<td>particle settling velocity ( \nu_{sT} ) at ( d_T ) in m/s</td>
<td>11.5</td>
<td>15.6</td>
<td>18.7</td>
</tr>
<tr>
<td>mass flow rate ( \dot{m}_{sT} ) in t/h</td>
<td>0.34</td>
<td>0.12</td>
<td>0.16</td>
</tr>
<tr>
<td>specific mass flow rate ( \dot{m}_{sT,A} ) in t/(m²·h)</td>
<td>8.5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>particle concentration ( \mu_{s,g} ) in g/kg</td>
<td>262</td>
<td>82</td>
<td>94</td>
</tr>
<tr>
<td>cut size ( d_T ) in mm</td>
<td>2.1</td>
<td>4.6</td>
<td>6.6</td>
</tr>
<tr>
<td>separation sharpness ( \kappa )</td>
<td>0.75</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>effective separation stages ( n_e )</td>
<td>1.8</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>utilisation of separation stages ( \eta_T ) in %</td>
<td>26</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>pressure drop ( \Delta p_{ZZ} ) in Pa</td>
<td>440</td>
<td>440</td>
<td>700</td>
</tr>
<tr>
<td>specific energy consumption ( W_{m,ZZ} ) in kWh/t</td>
<td>0.39</td>
<td>1.25</td>
<td>1.72</td>
</tr>
</tbody>
</table>
t/(m²·h) related to the apparatus cross-sectional area and the mass related energy consumption of only 0.4 - 1.7 kWh/t, Table 5.

5 Results of Gravity Aeroseparation

Tests on the separation of concrete-brick mixtures were carried out. Figure 4 shows the reproducibility of the separation efficiency on the basis of the results of four tests with a 15-stage unit, all conducted under identical conditions (d = 8 - 12 mm).

![Graph showing separation function T(ρs) vs. particle density ρs in g/cm³]

It can be seen that the separation results demonstrate considerable scattering in comparison with classification according to Figure 3. The plotted model curves limit the range of separation efficiency from κ = 0.67 - 0.91 for ne = 1 – 7, Table 6.

![Graph showing separation of concrete-brick rubble, d = 8 - 10 mm, n = 7]

From a comparison of the separation experiments with narrowly fractionated concrete-brick mixtures d = 8 - 10 mm (Figure 5), it can be concluded that this scattering is caused by the influence of the particle size. Representative for the other tests, Figure 5 shows that the separation model Eq. (6) can be fitted very well to the measurement results for narrow particle size ranges. The sharpness of this separation with the 7-stage unit can be rated as very good with κ = 0.86. The utilisation of the
seven apparatus stages $\eta_T = 54\%$ at an effective number of stages of $n_e = 3.8$ must be rated as satisfactory to good, Table 6.

![Graph showing separation function $T(\rho_s)$ vs. particle density $\rho_s$ in g/cm$^3$.](image)

Figure 6: Separation of concrete-brick rubble with rubber granulate, $\bullet$ d = 4-5 mm, $\Delta$ d = 5-6.3mm

On this basis, the layout for the separation of a lightweight fraction, here rubber granulate $\rho_s \approx 1.0$ g/cm$^3$, is relatively unproblematic, Figure 6. Because of high particle concentration $\mu_{s,g} = 417$ g/kg adjusted here, a comparably small specific energy consumption $W_{m,ZZ} = 0.19$ kWh/t is generally obtained for the good separation efficiency, Table 6. Satisfactory to very good results were also achieved in the difficult separation of a partially liberated aggregate consisting of hardened cement paste rubble, $\kappa = 0.66 - 0.94$ (31 1997, 1999) at utilisation coefficients of $\eta_T = 7\% - 87\%$.

Table 6: Assessment of the gravity separation results

<table>
<thead>
<tr>
<th></th>
<th>concrete-brick rubble</th>
<th>concrete, rubber</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Figure 4</td>
<td>Figure 5</td>
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<tr>
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<td>8 - 10</td>
</tr>
<tr>
<td>Channel velocity $u$ in m/s</td>
<td>14</td>
<td>12.5</td>
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<tr>
<td>Air volume flow rate $V'$ in m$^3$/s</td>
<td>0.56</td>
<td>0.51</td>
</tr>
<tr>
<td>Particle settling velocity $v_{sT}(d_T)$ in m/s</td>
<td>20.3</td>
<td>21.7</td>
</tr>
<tr>
<td>Mass flow rate $m_T$ in t/h</td>
<td>0.12</td>
<td>0.15</td>
</tr>
<tr>
<td>Specific mass flow rate $\dot{m}_{s,A}$ in t/(m$^2$·h)</td>
<td>3.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Particle concentration $\mu_{s,g}$ in g/kg</td>
<td>50</td>
<td>68</td>
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<tr>
<td>Cut density $\rho_{s,T}$ in g/cm$^3$</td>
<td>2.1</td>
<td>2.4</td>
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<tr>
<td>Separation sharpness $\kappa$</td>
<td>0.7 - 0.9</td>
<td>0.86</td>
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<tr>
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<td>1 - 7</td>
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<td>54</td>
</tr>
<tr>
<td>Pressure drop $\Delta p_{ZZ}$ in Pa</td>
<td>1600</td>
<td>815</td>
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<tr>
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<td>8.0</td>
<td>2.75</td>
</tr>
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</table>
6 Summary
To assess the efficiency of the separation of liberated aggregate particles of concrete rubble fragments, the separation functions were determined and compared with a theoretical model of multistage turbulent cross-flow separation. Specific mass flow rates 3 to 16 t/(m$^2$ ⋅ h) and mass related energy consumption 0.2 to 8 kWh/t were obtained. On the basis of the well-known separation sharpness, a considerable utilisation of separation stages as well as geometrical variability of a zigzag apparatus, it could be shown that this multistage cross-flow separation principle is well suited for the gravity separation of mineral materials.

7 Symbols and Indices

A  area
\( \text{A} \)  cross-sectional area related, feed

d  particle size
\( \text{d} \)  effective

g  gravity acceleration
\( \text{g} \)  fluid

h  channel height
\( \text{f} \)  fines

\( \text{m} \)  mass flow rate
\( \text{g} \)  gaseous

n  total number of separation stages
\( \text{G} \)  coarse

q  frequency distribution
\( \text{i} \)  particle size fraction

T  separation efficiency function
\( \text{j} \)  particle density fraction

u  fluid velocity
\( \text{K} \)  channel

\( \text{v} \)  particle velocity
\( \text{L} \)  lightweight

\( \text{V} \)  volume flow rate
\( \text{m} \)  mass related

W  work, energy consumption
\( \text{p} \)  particle

z  fraction number of separation stages
\( \text{o} \)  overflow

\( \alpha \)  exponent
\( \text{s} \)  solid, settling

\( \Delta \text{p} \)  pressure drop
\( \text{S} \)  heavy

\( \eta \)  utilisation coefficient
\( \text{t} \)  turbulent

\( \kappa \)  separation sharpness
\( \text{tot} \)  total

\( \mu \)  particle concentration
\( \text{T} \)  cut-point, separation

\( \xi \)  physical separation characteristic
\( \text{u} \)  underflow

\( \rho \)  density
\( \text{ZZ} \)  zigzag apparatus

8 References


6 Gorzitzke, W., Trockenes Sortieren grober disperser Feststoffe durch Kombination von Sie-