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Seminararbeit

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"Faszination Sand: Die Physik granularer Materialien"

Patterns in a flat rotating box

von
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Contents

Important symbols:

C	Fill level
Cc	Critical fill level
F	Froude number

Statement of authorship

I, Adrian Ebert confirm hereby that the work presented in this project thesis has been performed and written solely by myself and I have not used any other than the stated auxiliary means.

I especially confirm that I marked all literal and analogous adoptions from other works as such.

Raubling, 25.October.2015 Adrian Ebert

0.1 Deutsche Zusammenfassung

Wenn zwei Granulate mit unterschiedlichen Größen und Texturen in einen flachen Container gefüllt werden, der um seine Längsachse dreht, so entstehen darin Muster. Bei niedrigerem Füllvolumen, entwickeln sich vertikale Streifen. Bei höheren erscheint Konvektion, welche wie Rollen in der granularen Struktur aussieht. Das ist erstaunlich, weil abhängig von dem Füllvolumen fast keine Bewegung möglich ist und die Drehrichtung der Rollen nicht durch die Rotation der Zelle bedingt sein kann. Es sollte hervorgehoben werden, dass die Box über einen sehr langen Zeitraum rotieren muss, ca. 10h bei ungefähr 20 Rotationen pro Minute, um die besten Ergebnisse zu erzielen. Die zahlreichen Mechanismen, die zur Entstehung der sogenannten "Konvektionsrollen" führen wurden untersucht, dadurch ist es einerseits möglich umfangreiche Beziehungen aufzuzeigen, und außerdem erzeugt dies komplett neue Beobachtungen, die teilweise mit den Ergebnissen von der Universität Magdeburg übereinstimmen, aber manchmal auch neue Fragen aufwerfen.

0.2 Abstract

If two granulates of different sizes and texture are filled into a flat container rotating along its horizontal axis, patterns form inside. At lower fill levels, vertical stripes develop, at higher ones, convection occurs that looks like rolls in the granular structure. This is astonishing, because, depending on the fill level, nearly no movement is possible and the rolls' rotating sense cannot be caused by the cell rotation. It has to be pointed out that the box must rotate over a long period, ca. 10 hours at approximately 20 rotations per minute, in order to get the best results. The various mechanisms which lead to the development of the so-called "convection rolls" are examined, so it is possible to clarify amble connections on the one hand and, on the other, this generates completely new observations that partially concurred with the results of the research at the University Magdeburg, but sometimes also raises new questions.

0.3 Acknoledgement

Especially I would like to express my thanks to Dr. Matthias Schröter, Dr. Alexander Schinner, Dr. Andreas Kratzer, Dr. Silke Stähler-Schöpf, Prof. Dr. Axel Schenzle, Dr. Frank Rietz and Prof. Dr. Claudia Schäfle for their opinions, advices, support, and sharing their experiences and knowledge with me.

1 Introduction

"So schnell schießen die Preußen nicht" -This German saying roughly translates to "The Prussians don't shoot that fast". We use it when we want someone to slow down or rethink something and it fits perfectly into my work, because of two reasons: firstly, there have been a lot of things that slowed me down during my research. As a student, I simply lacked of experience in scientific tasks but choosing such a difficult topic, I was pretty much thrown into it. Furthermore, a long period of time had to be used for testing, so it took me nearly half a year until I had the first reasonable results. Secondly, the Europeans used black powder for their rifles in the 13th century. This explosive mixture was transported on lorries over bumpy roads which sometimes led to a de-mixing effect with a terrible outcome when finally shooting it[1].
Until today, granular material -to which black powder belongs to- is mostly not yet understood, although we have to deal with this topic in our everyday-lives. For example: have you ever wondered why the unloved raisins are always on top of your cereals? This phenomenon will be explained later, since it is well known and also caused the trouble with the black powder. Meanwhile I examined a way more complex and special mechanism concerning granular than that.
The first experiments were performed by Yositisi Oyama[2], an engineer who is considered one of the pioneers in granular physics. In 1939 Oyama made an astonishing observation when he filled a rotating drum to the half with limestone particles of different sizes. The smaller beads were then sieved out by the larger ones which leaves a stripe pattern within the drum. This experiment was later repeated by Frank Rietz and Oscar Stannarius who moved the work on pattern formation in granular material forward by using a flat rotating box, instead of a drum[3].

Figure 1: Stripe pattern with limestone particles in a rotating drum[4].

Since their experimental setup was extremely complicated, by far too expensive, and simply not realizable for a student, I searched for a substitute of their materials. The solution for this problem was then found in the work of Prashant Vipul who performed similar experiments with an easier setup and by using mustard and poppy seeds, instead of expensive glass beads[5]. Surprisingly, Vipul got reasonable results but did not, at least as far as I know, push this work forward and also never published it. Still, he proved that it was

[1]Morsch Oliver: Sandburgen, Staus und Seifenblasen. Weinheim, Wiley-Vch, 2005, 35.
[2]Buchaman, Mark (2015): Drum roll
http://www.nature.com/nphys/journal/v7/n10/full/nphys2115.html.
[3]Rietz, Frank (2012): Convection and segregation of beads in a flat rotating box. Hereafter referred to as *Convection and Segregation*.
[4]Convection and Segregation, 7.
[5]Prashant, Vipul (2011): Pattern Formation in Granular Materials, private communication.

absolutely possible to gain patterns in a flat rotating box with a basic setup. Together with the quote,

> ”Even relatively simple equipment can produce rich varies of novel and challenging experimental phenomena that are beyond our current understanding[6].”

by Frank Rietz, I had enough motivation to give it a try myself, although there has never been such an experiment with material, a student has access to.
But what is ’convection’ that is mentioned in the title? Convection has a huge number of different forms, it cannot only be found in physics, but also for example in geology. Concerning this sector, convection pattern was found in rock beds, created by the movement of continents. Although it is not completely clear why rock beds move at all. However, it is proposed that the most common form, the thermal convection, drives this phenomenon. Let’s go to a simpler everyday example: what happens inside the pot when you are cooking water for your morning tea? The herd heats the bottom of the pot, if we assume that the middle of the plate is the hottest point, the water there will rise to the surface. Of course it has to go somewhere once it is cooled down, because of thermal conductivity with the air, so it will sink again to the bottom along the walls of the pot. What you now have are convection rolls inside the fluid. Similar to this example convection rolls can also be seen in the rock bed and in granulate with which I experimented.
However, at the beginning it had to be figured out, whether it was possible for me to get such patterns, at all. Another important problem was how to record the pattern formation, because a single run takes about 10h. Even if anyone had enough time to write down every change in the box, you still have to watch the movement multiple times, in order so see the different flows.

[6] Convection and Segregation, 6.

2 Setup and execution

Although three setups had to be built during testing to improve the outcome, the specifications of the boxes were mostly identical. Of course there was not always the same container in use. Just as the setup, the box had to be built in different versions, using diverse material and methods of manufacturing, in order to get the best results. The simple figure 2 illustrates the rotation, while the dimensions itself are explained in the section ”Container geometry”.

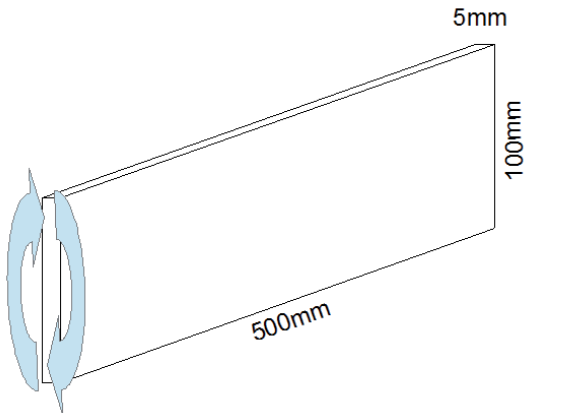


Figure 2: Shematic sketch of the container rotation.

In order to compare the results there have often been three runs with the same settings. The duration differs but a single run took at least 10h with 20rpm, to ensure 10.000 rotations or more (The minimum amount of rotations was taken from Frank Rietz's experiments, as well as the number of photos taken which means, their frequency.[7]). The photos were taken every 20 rotations and always from the same side of the container, except in those cases necessary[8]. In most instances the pattern formations on both sides were equal, as soon as the starting process was over and the granulate rather fluidized.
Finally, the last version of the cell was, by far, the most complicated. Since records of the movement within the box were necessary, a camera was attached which had to be perfectly timed with the rotation of the box. To ensure that, a light barrier had to be connected with the trigger mechanism of the camera. Figure 3 shows the circuit diagram of the whole system.

[7]Cp. Convection and Segregation, 16.
[8]Cp. *ibid.*

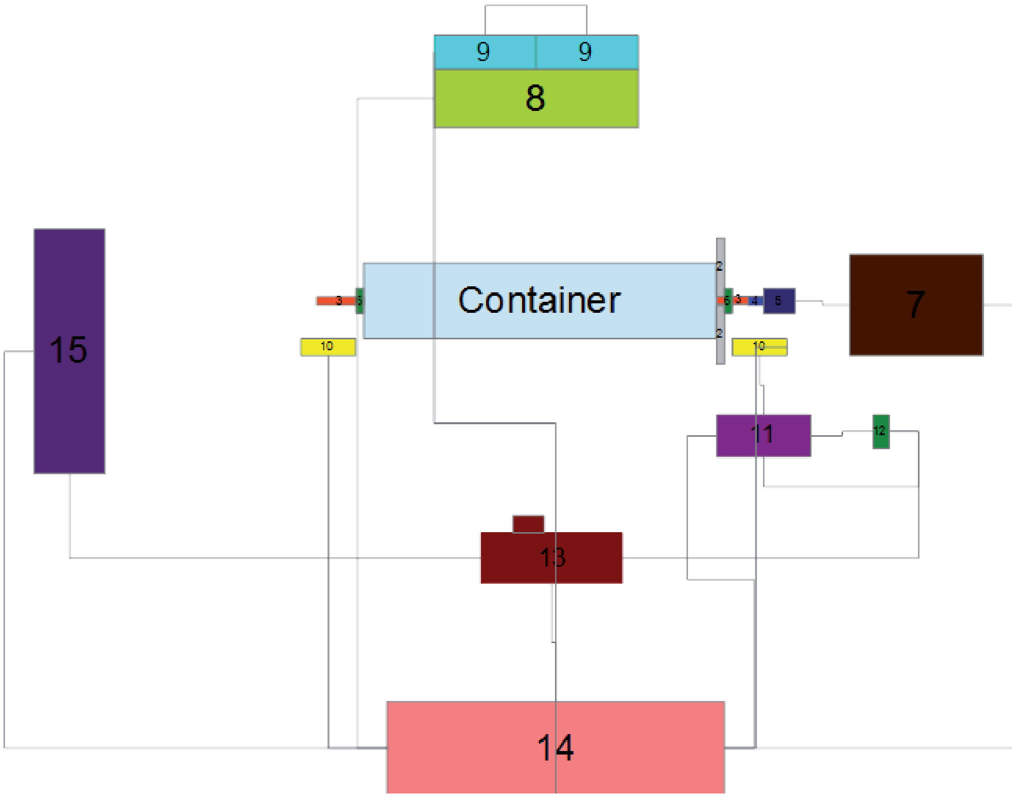


Figure 3: Schematic sketch of the setup.
2. Interrupter, 3. Axis, 4. Connector, 5. Motor, 6. Ball-bearing, 7. Voltage regulator, 8. Lamp, 9. Fans, 10. Photo transmitter and receiver, 11. Arduino micro controller, 12. Transistor, 13. Camera, 14. Power supply, 15. Storage computer

The rotation speed is controlled by voltage. The interrupter plates cut off the connection between photo transmitter and receiver that is wired with the Arduino micro controller. The controller is programmed to count the interruptions and sends a signal to the transistor which then closes the circuit of the camera trigger mechanism. Using this simple method allows to take perfectly timed photos, although it, again, took quite a while of trying and fails. It has to be pointed out that the rotation speed is not nearly as accurate as the one Frank Rietz is able to achieve. He measures the frequency of interruptions and the voltage that controls the motor is then automatically adjusted[9].
In contrast to the composition of Frank Rietz, my box was rotating with constant speed, meanwhile he used to slow his container down for every picture[10]. According to him, it does not make a difference, whether the box is halted at any moment, because the whole pattern formation depends on the starting conditions and not on the dynamics, except for the parameters, of course[11] [12].

[9]Cp. Convection and Segregation, 17.
[10]Cp. *ibid.*
[11]Cp. *ibid.*, 90.
[12]Except for particular rocking motions (Cp.*ibid.*).

Figure 4: Pictures of my setup.

3 Different pattern formations

Basically two different types of pattern formations are of great importance. The first one is the axial segregation which looks like vertical stripes and works with the same principle as the formation in the rotating drum. The smaller particles are sieved out by the larger ones[13]. The second, and by far more complicated one, is the formation of convection rolls on whom my work initially should have been based on. Both can be seen as phases, because their appearance depends on the fill ratio "C" of the container[14]. This will be explained more in detail in the section "Fill ratio". The mechanism and my results for axial segregation are explained in the following, while the convection rolls need some extra knowledge and are thus treated later in the section "Convection mechanism".

3.1 Axial segregation

Figure 4 shows examples for axial segregation with the typical stripe pattern. Actually this only occurs at lower fill levels[15] but in this case no convection rolls were visible, although the container was highly filled. This might have to do with the huge difference of the two sizes of the granulate, the mustard seeds and the salt. An important issue connected with this experiment will be mentioned in section "Different material". Figure 9a that is used to explain chute flow shows the plotted movement of grains inside a box in which axial segregation occurs.

3.2 Convection rolls

The phrase convection roll should not be taken literally. In fact they always occur when convection is present but it is not possible to distinct what a single roll actually is or how they look like. They can have many different forms, be compact and square, or large and stretch through the whole container. Because of this it is so difficult to examine them. The pictures in figure 6 show some examples for convection rolls and should be seen as an contrast to the axial segregation. Also the graphs from the tracers are more difficult to understand.

4 The mechanisms of movement within the box

There is a large number of different mechanisms within the container which can be used to explain the pattern formation. The mechanisms are relatively well understood, their impact however is not that easy to extinguish, thus it is not possible to explain the circumstances that lead to the patterns for sure.

[13] Cp. Convection and Segregation, 27.
[14] Cp. *ibid.*, 33.
[15] Cp. *ibid.*, 27.

(a) ca. 2500 rot.

(b) ca. 7600 rot.

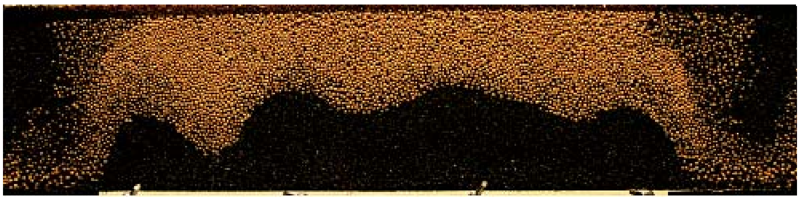
(c) ca. 11100 rot.

Figure 5: Experiment 16.1. Axial segregation in large segments and their transition can be seen here.

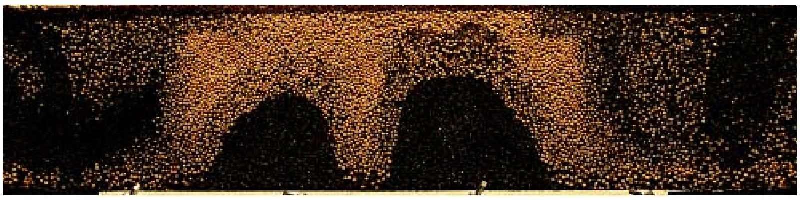
4.1 Global convection and chute flow

At first I would like to explain the easiest mechanism: as soon as the granulate reaches the top, the grains at the new front plate begin to fall down a bit earlier than the ones at the back, this forms a global convection in the same sense as the rotation of the container itself[16]. The sliding of the grains is described as "chute flow"[17] which plays an important role especially in boxes with lower fill levels, because the granulate can move more freely, this directly influences the formation of convection rolls, "Even moderate chute flow in the container at lower filling ratios will eliminate the convection mechanism"[18].

[16] Cp. Convection and Segregation, 10.
[17] Cp. *ibid.*
[18] *Ibid.*, 89.

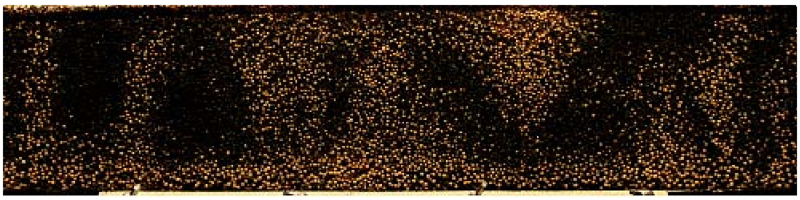


(a) ca. 1800 rot.

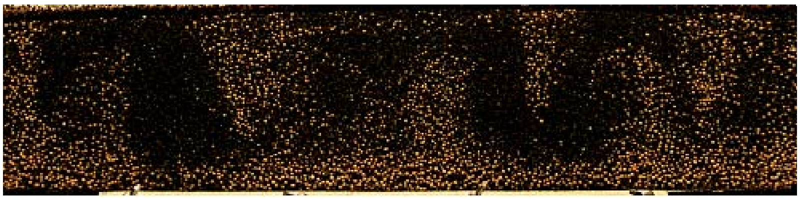


(b) ca. 2700 rot.

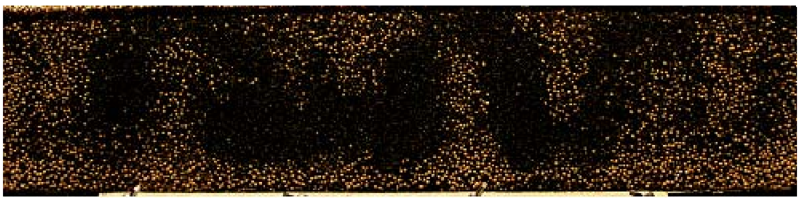
(c) ca. 3600 rot.



(d) ca. 5200 rot.

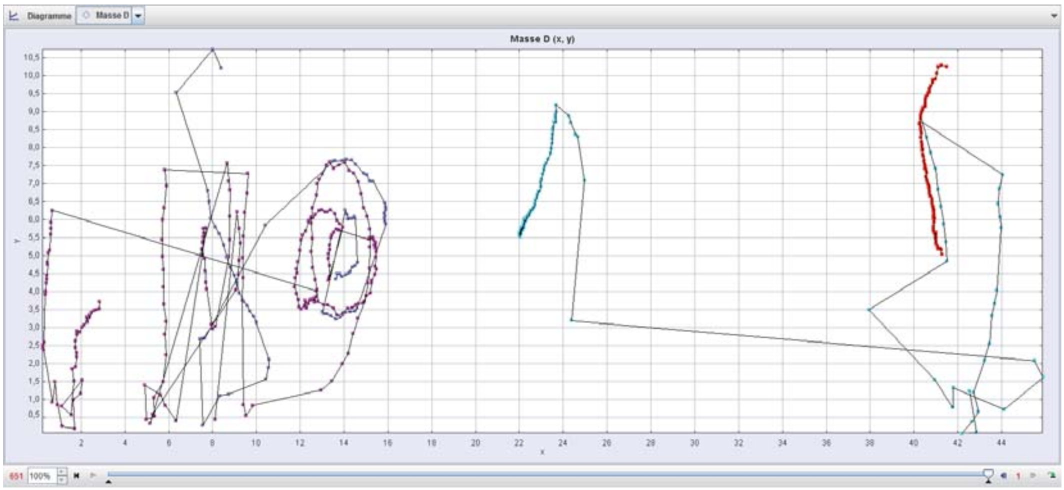


(e) ca. 9200 rot.

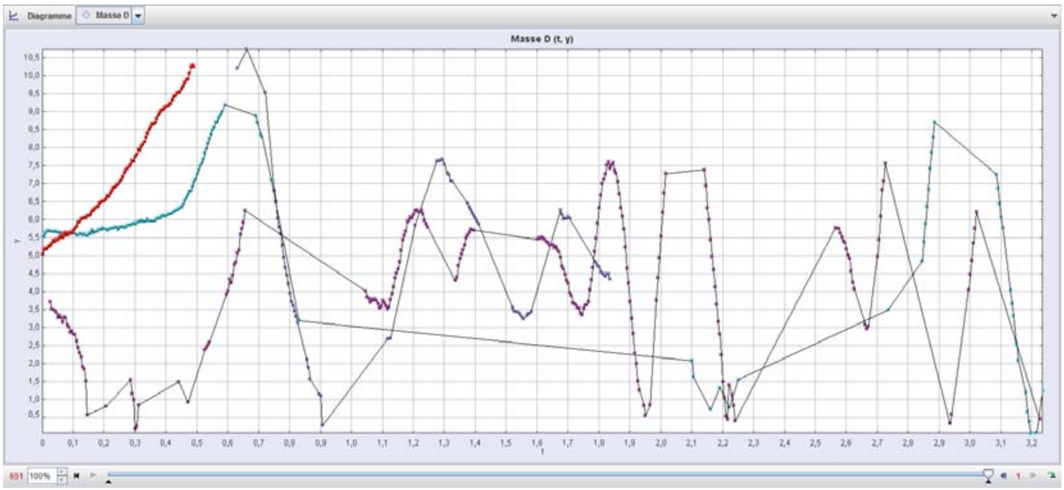


(f) ca. 14100 rot.

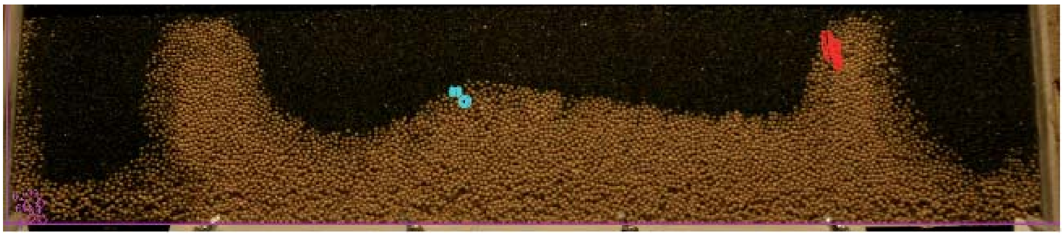
Figure 6: Experiment 14.3. In this case very distinct convection rolls occur. The snake pattern after a few thousand rotations typically indicates convection. While there is one large roll at the beginning (figure 6c), later various convection patterns can be found. Typically the smaller granulate is in the middle and the bigger beads are on the outside, similar to the double brazil nut effect, described in section "Air humidity".



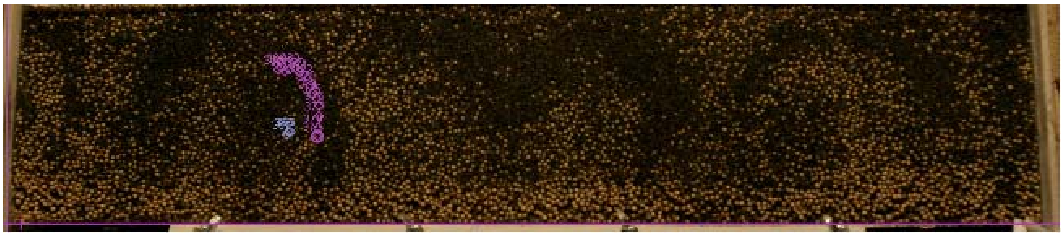
(a) Movement in x- and y- directions.



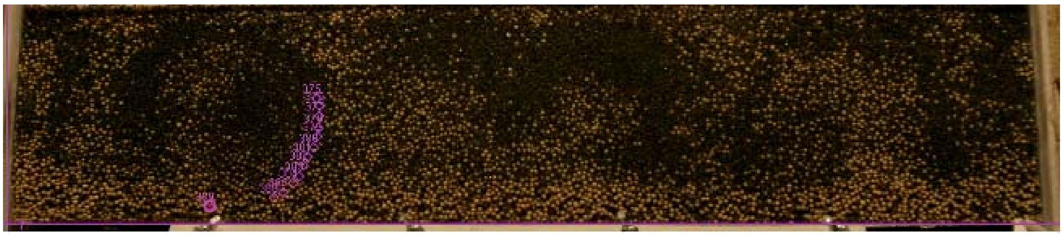
(b) Movement in y- directions and time.



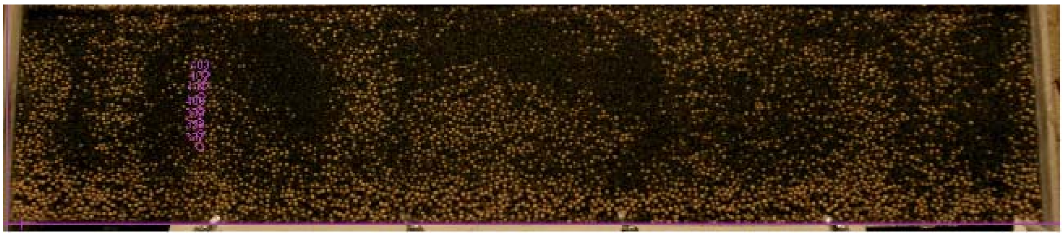
(c)



(d)

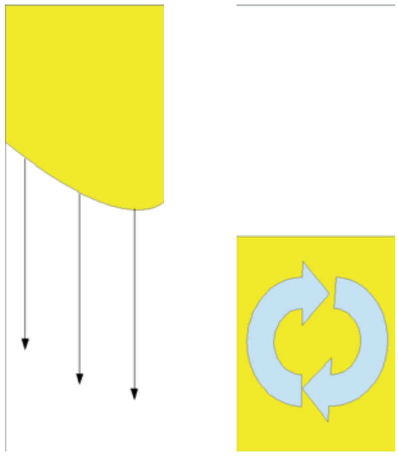


(e)



(f)

Figure 7: The graph in figure 7a can be seen as the whole container. The movement of several tracers were plotted, the violet one for example is directly inside of a convection roll. 6b shows the movement in y-direction and the time. This is important, to understand some motion that would otherwise seem extraordinary. The red line for example would usually be too straight for a container with convection, but the red tracer could just be tracked at the beginning of the run. Because there is less movement during the starting process, thus no instant rotation, the path is straight.



(a) (b)

Figure 8: Chuteflow, explaining global convection. Movement is in the same direction as Rotation of the box[19].

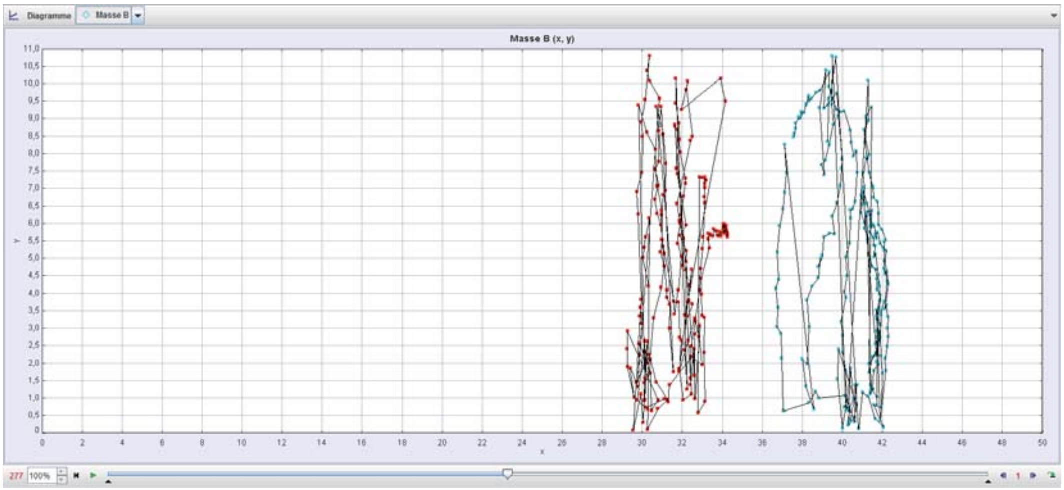
In later experiments the software "tracker[20]" was used to determine the movements of single particles. For this reason the bigger grains, in the majority of cases mustard seeds, have been coloured and this way treated as tracer particles. In experiments with interesting results, the tracers were then tracked manually which means to go through every single of the 500 to 800 pictures and mark the coloured mustard seeds. The software would then plot the data, as shown for example in figure 7. These plots allow to prove various mechanisms, although it is not possible to recognize every convection roll, as planned. It has to be said that a qualitative analysis based on data does not seem to make sense, because the pattern formations and movements are by far to complex to be reduced by numbers and can only be analysed by description.

The chute flow is surely influenced by the material the container is made out of. I will explain this later in section "Impact of the container material".

4.2 Fluidized Edges

Usually the convection rolls start from both lateral walls and then continue throughout the cell. The edges can thus be seen as "fluidized". This phenomenon might have to do with the filling procedure, as Frank Rietz proposes[21]. Although the box has to be filled very equal and always with the same method, slight differences cannot be avoided. Furthermore, after filling, the granulate often forms a "pile" which has to be made even. Further experiments should prove the importance of filling and starting condition and slight variations, as can be seen in section "Further experiments".

[19]Adapted from: Convection and Segregation, 11.
[20]Link to the download: http://www.opensourcephysics.org/items/detail.cfm?ID=7365.
[21]Similar to a shaken container (Cp. Convection an Segregation, 40).

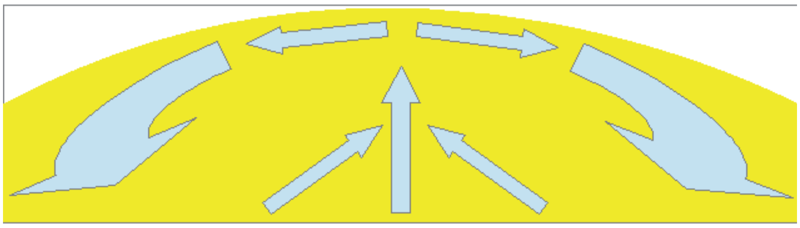


(a) Screenshot of the Tracker software with two particles that move in perfectly straight lines

(b) The tracked particles shown together with the actual cell. The axial segregation that goes together with this pattern is better shown in figure 5 which comes from the same experiment.

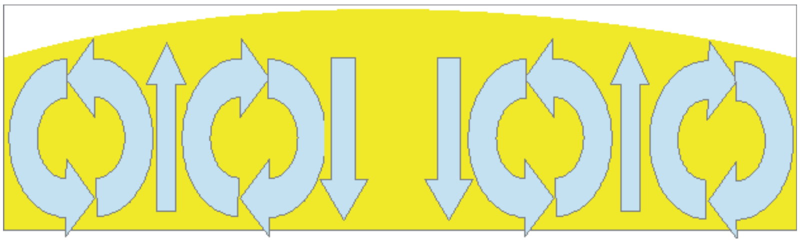
Figure 9: Plotted movements of the grains. The whole coordinate system can be seen as the container. In this case the grains just moved down on very straight lines which proves the global convection. Figure 6 shows the contrast to this axial segregation which is of course connected with the global connection, as already explained.

Figure 10: This screen shot shows that the particles are often whirled around in the fluidized zones at the top and bottom which I will treat in section "Horizontal fluidized zones"



(a) Convection at the fluidized edges in lower filled containers, similar to a up and down shaken boxes.

(b) In higher filled cells the convection rolls are more compact and mostly occur at first at the fluidized edges, perhabs because of the filling procedure or because of the lower friction to the lateral walls.



(c) The rolls at both cell ends create a flow that pushes trough the whole container wich leads to other convection rolls.

Figure 11: Schematic sketch of the fluidized edges and their possible influence on the convection rolls[22].

Another reasonable explanation for the strong movement on both side walls could be the smaller friction to the acrylic glass in comparison to the friction to other particles, so it is easier for the beads to move along the edges[23].
In comparison to the convection in shaking containers, shown in figure 11 a, the edges "may play a certain role for the convection pattern (they fix the wavelength), but they are not necessary for the formation of the convection structures"[24], as Frank Rietz puts it.

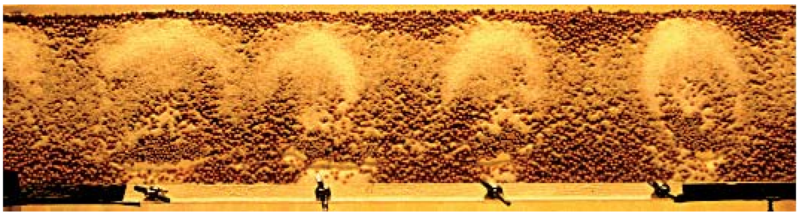
4.3 Horizontal fluidized zones

There are not only fluidized zones at the side walls, but also along the top and bottom boundary. In these regions the granulate moves somewhat faster and also circulates in the same direction as the cell rotation[25], meanwhile there is

[22] Adapted from: Convection and Segregation, 40.
[23] Cp. *ibid.*, 10.
[24] *Ibid.*, 42.
[25] Cp. *ibid.*, 90.

only very small movement in the middle part of the container. These observations are just valid for higher fill levels, because of the small movement and the bigger friction, the beads can hardly move. While the granulate flows as a whole at lower fill levels, at higher ones only single particles are able to change their position.
It is suspected that there is a kind of sieving, similar to the axial segregation along the horizontal fluidized zones[26]. Although I could not quite confirm this theory, it seems to fit perfectly with other of Frank Rietz's observations, but he also assumes that the differences in height and density are a lot smaller than in axial segregation. However, if there is a sieving in the fluidized zones at the top and bottom walls, this will lead to differences in density and height, just as shown in section "Axial segregation". This is of huge importance, because other experiments showed that if the top and bottom walls are manipulated by installing gaps or rather pieces of acrylic glass, the convection rolls will most likely form at these regions[27]. In fact, I randomly made a similar observation when I used mustard seeds and salt: because of the size differences the salt filled the gaps between the mustard seeds and the walls which made the material stuck. This created regions in regular distances where less movement was possible. And as it turned out, these regions were exactly the origins ot the convection rolls. (The granulate was only stuck underneath the places a screw was positioned, since the pressure there is a bit higher which does normally not affect the pattern formation).

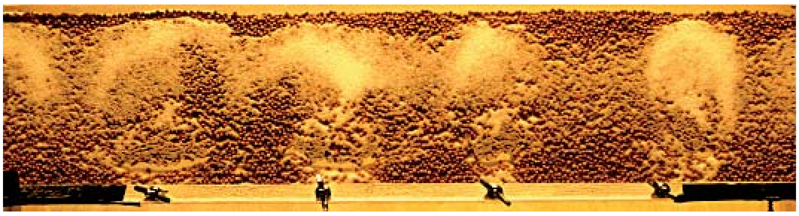
[26] Cp. Convection and Segregation, 91.
[27] Cp. *ibid.*, 45.



(a) ca. 3000 rot.

(b) ca. 4000 rot.

(c) ca. 10100 rot.



(d) ca. 14000 rot.

Figure 12: Accumulation of salt where the screws are, because some material there is stuck which creates less space.

Furthermore, it should be mentioned that the circulation sense of the fluidized zones differs if the cell does not rotate continuously but is moved back and forth in a rocking motion, which means the rotation sense is reversal every half turn. In that case the sense of circulation will reverse in one of the two fluidized zones. When the direction is changed every 360° no clear convection in the fluidized zone is visible[28].

[28] Cp. Convection and Segregation, 90.

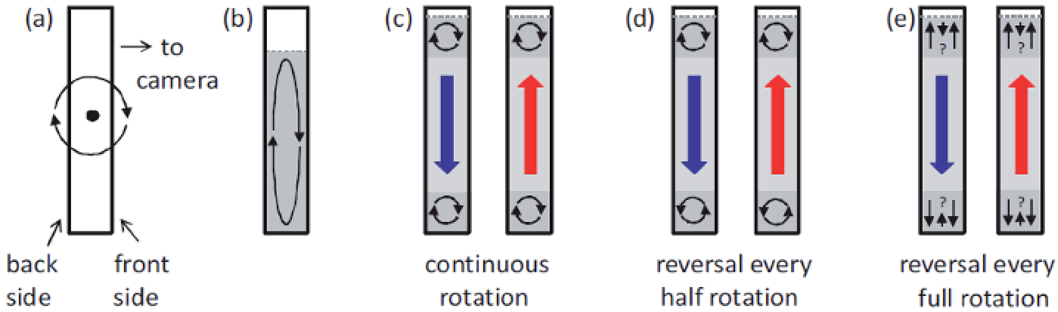


Figure 13: Convection as a result of cell rotation[29].

4.4 Convection mechanism

Quite obviously there are a lot of factors that influence the convection, thus the question is: how do the diverse mechanisms within the cell work together in order to build convection rolls? The key to the understanding of their origin seems to be the transition between the two phases (figure 20) which is, of course, directly connected with the fill level and Cc. The fill level is also the most easily controllable parameter. At first we should take a look at how these mechanisms are influenced: at lower fill ratios global convection will appear and with that also chute flow, eliminating convection rolls, as stated by Frank Rietz[30]. On the other hand there are several mechanisms that will only occur at higher fill levels. Firstly, the horizontal fluidized zones can just develop when the movement of the granulate is small enough (subcritical fill level)[31] [32]. As already mentioned, a sieving effect similar to axial segregation in these regions are probably responsible for the density differences[33]. This will lead to more and less packed zones in the box which is probably one of the main driving principles for convection and can be explained as this: the particles in the denser packed regions will, of course, travel to looser ones as shown in figure 13. The convection formation in momodisperse material might be explained with the rolls that start at both lateral walls. This would explain, why the formation of convection is way less effectively in monodisperse granulate, but not impossible[34]. Frank Rietz also proposes that this circulation (figure 14) can be seen as up and down forces[35]. One might think they have to be larger than the gravitation that pulls the particles down with every rotation but at higher fill levels, there is, of course, gravitation as well, but no movement downwards as a whole. The particles can not fall down when the packing of the cell is to high. This observation may explain why chute flow eliminates the convection. To sum it up, the up and down forces that origin from the convection at the lateral walls and the density differences at the horizontal fluidized zones at top and bottom can probably overcome the gravitation and prevent the

[29] Adapted from: Convection and Segregation, 90.
[30] Cp. *ibid.*, 89.
[31] Cp. *ibid.*, 26.
[32] Cp. *ibid.*, 90.
[33] Cp. *ipid.*, 91.

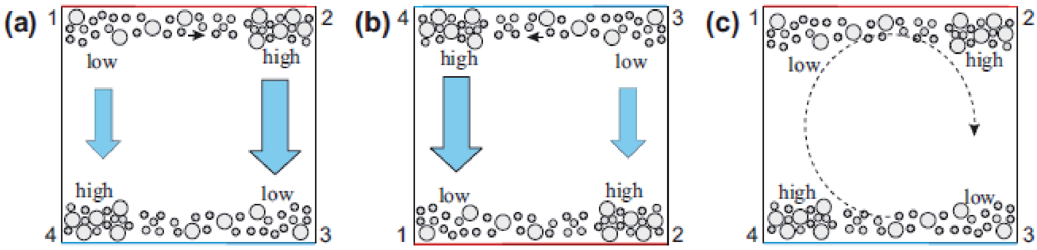


Figure 14: As a result of sieving there are density fluctuations along the horizontal boundary (red and blue lines). The particles are equally dragged down by gravitation, but the beads in denser packed regions (2) will flow down faster than the looser ones (1). After a 180° rotation (figure 14b), the blue border is on top and the situation is now reversed: the beads in the denser zones (4) are pulled down faster then the other ones (3). In order to compensate this flow, the granulate will also move in x-direction from the denser to looser packed regions. This forms a circle within the box [37]. Of course there is one question left: why are the spots with the same density exactly diagonal opposite? The explanation for that can be found in the slope and backflow of the granulate (figure 15).

particles from moving down and pull them upwards instead. This can just work whenever the beads cannot fall down due to the higher packing of the cell. However, this explanation is just a theory that seems to concur with the observations of Frank Rietz and myself.

[34] Cp. Convection and Segregation, 53.
[35] Cp. *ibid.*, 90.
[36] Adapted from: *ibid.*, 93.

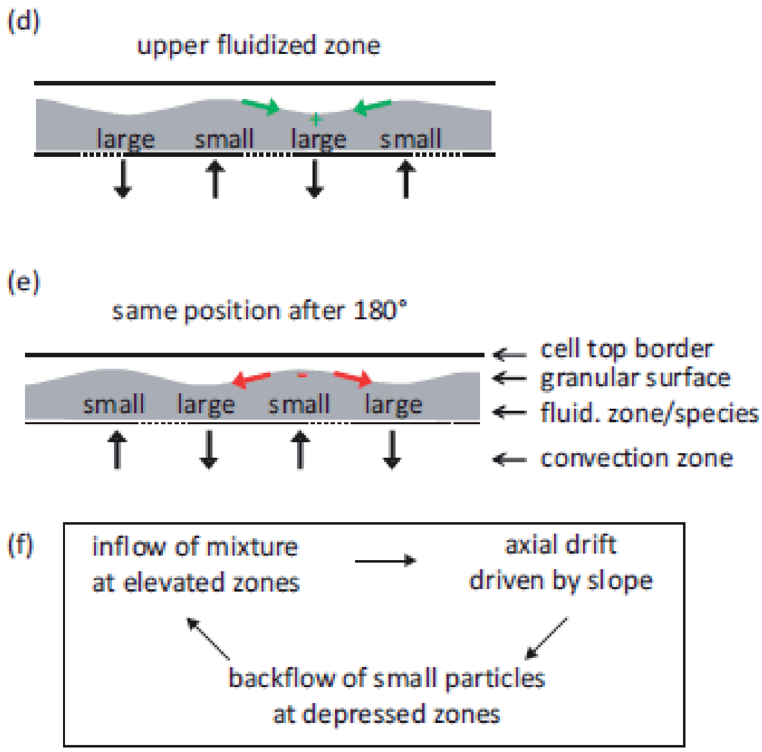


Figure 15: This figure sketches the situation in the horizontal fluidized zone at the top: due to the differences in density, also the height in the horizontal fluidized zones differ. The smaller beads are usually elevated, because of that, they will fall down and gather in the valleys of the larger beads. After 180° (figure 15 f) there will be a hill at the same position where the former valleys have been. Hence, the smaller particles will always falls down from the elevated zones, creating a shift from approximately the half size of a convection roll. 14 f shows this circulation[38].

5 Different parameters

5.1 Impact of the container material

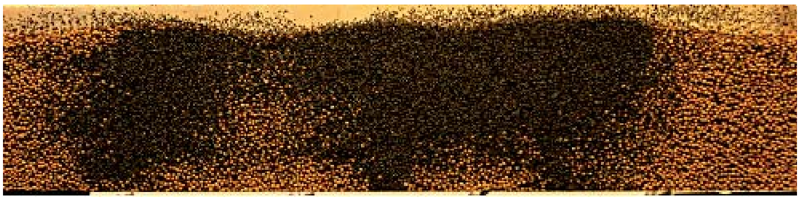
The material used for the container influences several aspects. For example the chute flow and with that also the global convection. Both depends on the friction of the wall. But until now, only acrylic glass was used, since it is easier to work with than normal glass. Experiments with a container made out of glass would be interesting, because plastic produces an electrostatic charge. This effect can be controlled by the humidity within the box[38]. It can be assumed that a high percentage of water has an de-charging effect. Because of this a hygrometer was used to measure the humidity in the room which was between 60% and 80%. In later experiments an air dehumidifier lowered this

[37]Adapted from: Convection and Segregation, 92.
[38]Cp. Convection and Segregation, 95.

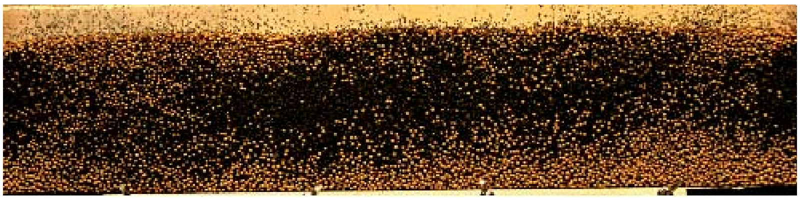
number in order to see the differences, these results are shown in the section "Result comparison".

(a) Experiment 11.1

(b) Experiment 12.1



(c) Experiment 12.2

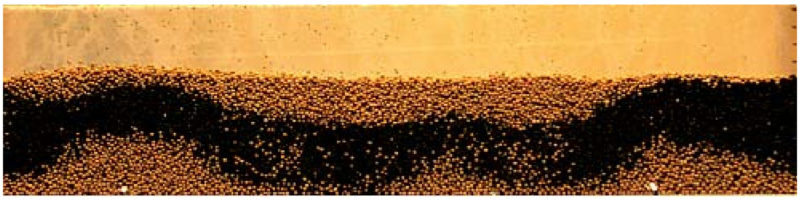


(d) Experiment 13.1

Figure 16: In order to show the electrostatic charge, experiments with lower fill levels were chosen. On the one hand, there is more movement which creates more static forces. On the other hand, the particles that stick to the walls would not be visible otherwise.

These pictures (figure 16) are a few examples for the electrostatic forces within the cell. It can be supposed that it is getting stronger, the larger the chute flow is, because of the bigger friction with the acrylic glass. Furthermore, as it is also shown, only the smaller particles are influenced by these forces and nearly stick to the material. Experiments with salt instead of sand or poppy seeds did not show anything like that, this might be one of the reasons for the completely unexpected results with salt (figure 12). But the electrostatic charge does not only come from the friction with the acrylic glass. Also during the emptying and filling procedure the granulate had a lot of contact with plastic material and there is also always friction amongst the particles themselves. In fact, when plastic cups or similar equipment was used, the beads often sprung out of their canister, once it was raised. In order to avoid that, it should always be tried to de-charge the particles with a metal spoon, or something similar.

5.2 Rotation speed



(a) Experiment 10.1, radial segregation at low fill level and slow rotation speed.

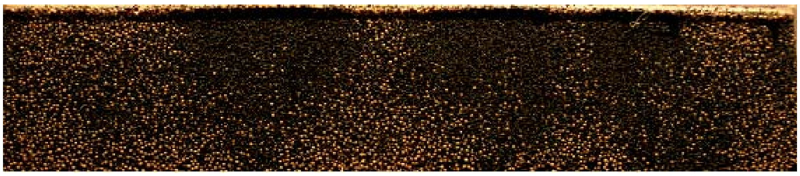
(b) Experiment 14.1, radial segregation at the beginning of a run, bevore transition to convection rolls.

Figure 17: Radial segregation at low rotation speed, influenced by up and down forces and fluidized edges.

The speed of the cell rotation plays an important role, since it influences the inertial forces. It furthermore defines the duration of the whole experiment and its outcome[39]. Because of that, the perfect rotation speed had to be figured out at first. It was found at 20rpm when the results seemed to be best. The inertial forces are expressed with the Froude number, which can be calculated with $F = \frac{\omega^2 * r}{g}$[40]. In order to gain the wanted patterns, this number has to be relatively low, Froude is at 20rpm for example only 0.01[41]. Interestingly Convection still occurs at 50rpm, but if Froude is bigger than 1, the inertial forces become too strong[42]. In this case, a radial segregation is visible, with "the segregation partly 'frozen' in the top/bottom regions", as Frank Rietz puts it[43]. According to him, an extraordinarily slow rotation speed just extends the duration of the experiment but does not influence the pattern formation[44].

[39]Cp. Convection and segregation, 35.
[40]*Ipid.*, 10.
[41]Cp. *ipid.*, 35.
[42]Cp. *ipid.*
[43]*Ipid.*
[44]Cp. *ipid.*, 35.

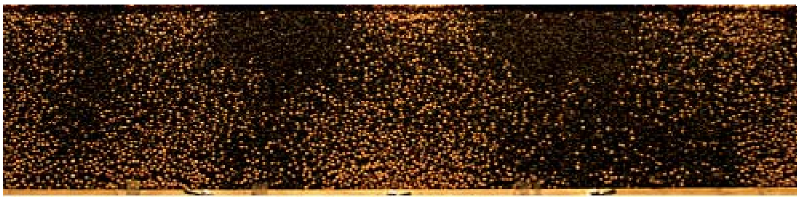
(a) Experiment 3.3, 13 rpm.



(b) Experiment 4.1, 20 rpm.

(c) Experiment 5.1, 47 rpm.

(d) Experiment 6.1, 25 rpm.



(e) Experiment 7.1, 15 rpm.

Figure 18: The pictures were taken after ca. 6000 rot. They show the impact of the rotation speed, although the results do not seem to differ a lot, the films make visible that the best outcome can be gained with 20rpm. This does not refer to the inertial forces, since the Froude number is by far lower than 1. However, it should be kept in mind that slight differences in rotating velocity directly influence the duration for the chute flow. Whether three or two stripes will occur cannot perfectly credited to this parameter, because errors and troubles can never completely be avoided. This can often lead to different results, yet they should not differ in an astonishing manner.

Although it is suggested that radial segregation occurs only at high inertial forces[45], this can also occur at lower rotation speed. It seems to be a kind of double brazil-nut-effect: in a shaken container, the bigger particles travel to the top. This might seem surprising, since everybody would expect that the larger and heavier ones move to the bottom, but the smaller granulate can

[45]Cp. Convection and Segregation, 35.

easily fill the space underneath the larger one in a ratchet-like effect[46]. By the way this phenomenon is also described in the introduction and led to the segregation in the black powder. This could be a main driving mechanism together with the up and down forces that are treated in section "Convection rolls" it might be an explanation for the pattern formation that occurs mostly at the beginning of a new run.

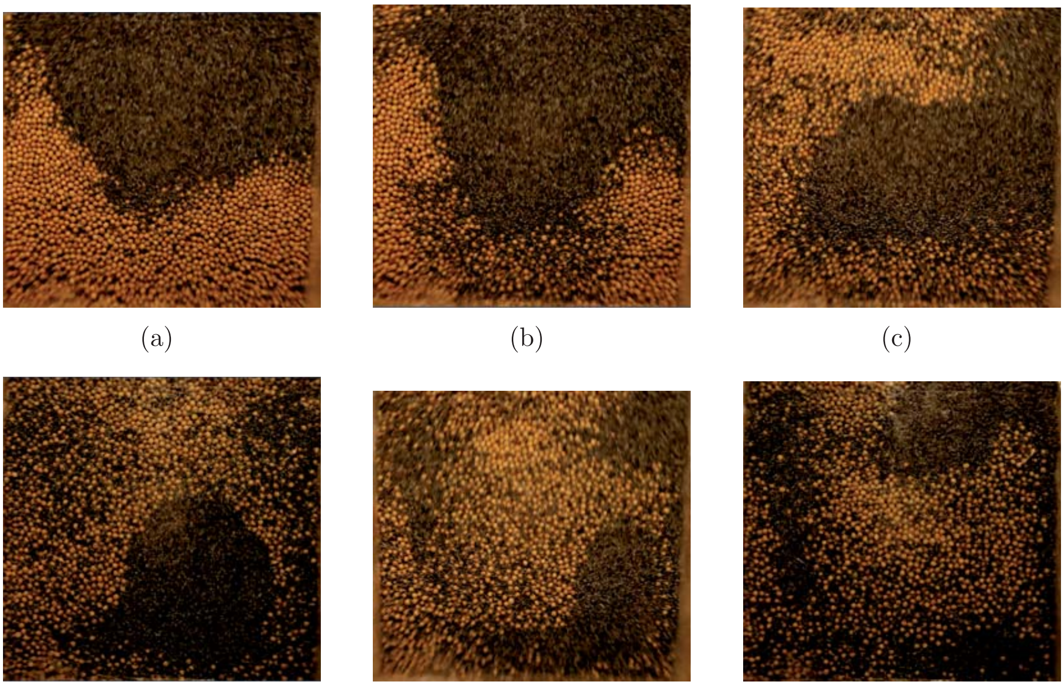
5.3 Container geometry

For my experiments containers with the specifications of 12cm x 50cm x 0.5 cm were used. The Cell aspect ratio[47] is defined by x/y which leads to 4.17 in this case. The length of the box defines the wavelength[48] which means, how many convection rolls or stripes fit inside of it. Meanwhile these patterns are nearly always as high as the cell, concerning y- dimension. Normally the patterns form very symmetrically throughout the container, but in my early experiments there have often been three stripes/ rolls on the same places, but they were not symmetrical (figure 16 a,b). This observation can be explained by assuming that the wavelength simply could not fit into the cell. Hence, if the container was a bit longer or shorter, symmetrical results would be found. In general, it can be said that the convection rolls are mostly square, thus a cell with $x = ky, k \in \mathbb{Z}$ would be desirable.

5.4 Single rolls

My work, however, did not focus on different container specifications, since the efforts and the costs would have been to high, because for every variation a new container would have been to be built. During the very early testing phase I managed to get a convection roll by using a CD case as a container. On the one hand, this proves with how primitive setups interesting results can be achieved, and on the other hand, this is an example for a single roll[49]. As a matter of fact the observations made completely accord with Frank Rietz's descriptions. According to him, "The circulation of grains produces nonuniform segregation patterns of the mixture that in turn interact with the convective ow. Oscillatory modulations of the convection velocity, cessations and spontaneous reversals of the circulation are observed."[50] This is exactly, what happened inside the CD-Case, especially surprising was the inversion of the rotation sense. Furthermore, it seems to be assumable that the segregation in boxes with cell aspect ratio 1 will reverse if the rotation velocity is changed. For slow speed the smaller particles will gather in the middle, while it is the other way around for higher velocities, similar to spheres filled with granulate[51].

[46]Oliver Morsch: *Sandburgen, Staus und Seifenblasen.* Weinheim, Wiley-Vch, 2005, 44.
[47]Cp. Convection and Segregation, 41.
[48]Cp. *ibid.*, 42.
[49]Cp. *ibid.*, 55.
[50]*Ibid.*, 55.
[51]Cp. *ibid.*, 75.



(a) (b) (c)

(d) (e) (f)

Figure 19: Experiment CD, a single roll inside of a nearly square (cell aspect ratio = 1) CD case. Reversal rotation sense of the convection roll is visible.

My goal was to take a closer look at 3d experiments, thus the cell should be broad enough for multiple layers of beads, so they can move back and forth. 2d experiments[52] are much more difficult to do, because the cell has to be broad enough for beads of different sizes, but must not allow the smaller particles to overlap. Because of that no real life experiments have been performed, yet.

5.5 Fill ratio

The fill ratio plays an important role for the wanted patterns. Thus, at first "it is necessary to define a quantitative measure for the fill level. The motional degrees of freedom of the granular particles are controlled by the available space above the granulate. However, this free volume is not a practicable parameter, since the height of the granular bed depends on the filling procedure, and it is not exactly preserved during the experiment."[53] Because of that reason the fill level was defined, as $C = \frac{m}{\rho * V}$[54] Hence, it is necessary to measure the material density, its mass and the Volume of the whole container, to gain a valid unit of measurement for the free space.
The free space defines which of the two phases, the axial segregation or convection rolls will most likely occur, since it also defines how much movement is possible. As already mentioned, this directly correlates with the chute flow that, when it appears, will eliminate the formation of the convection rolls[55].

[52] Convection and Segregation, 75.
[53] *Ibid.*, 25.
[54] Cp. *ibid.*
[55] Cp. *ibid.*, 89.

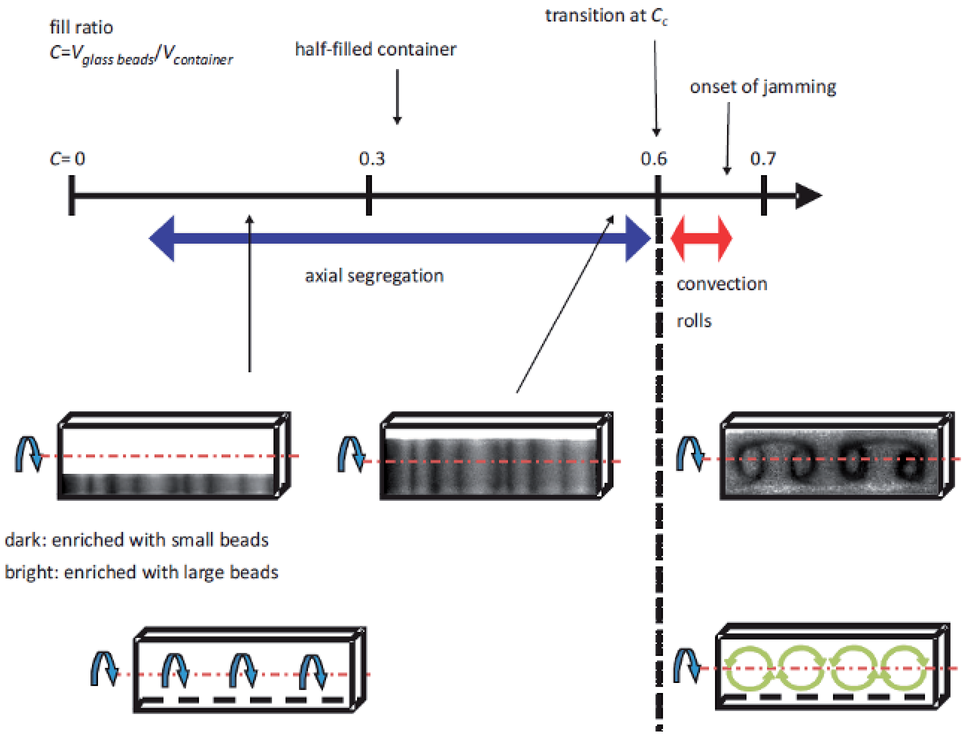


Figure 20: Which phase is most likely to occur, depends on the fill level. This can be seen as a transition of phases. However, in some cases none of these patterns will form[57]

.

In general it can be said that the "critical fill hight Cc"[56] is at approximately 95-98% of the container volume. In my experiments this is about less than 1cm. since Frank Rietz uses much smaller granulate, he aims at 0.3-3mm[57]. The connection between particle size and Cc can be explained like this: after starting the cell rotation, the smaller beads will slide into the gaps of the larger ones during the first turns. On the other hand, the granulate will expand in this period, although there is nearly no movement. In reality this means that the volume of the granulate will at first expand, and later, when it is more or less fluidized shrink. To allow the slight movement at the beginning, at all, the height of the free space must be appropriate for the size of the granulate and a multiple of it, with the factor of round about 10.

5.6 Different material

The biggest problem concerning finding the right material for the granulate is not actually finding them, but separating them after each run. Prashant Vipul built a sieving machine out of this reason and also to improve the equality of the beads. However, this would have gone too far for my work, so I used granulate, large enough and with a difference in size that allows to be separated manually with a simple kitchen sieve. The equality of the beads is an interesting aspect, so it can, for example, be assumed that small differences

[56] Convection and Segregation, 26.
[57] Cp.*ibid.*

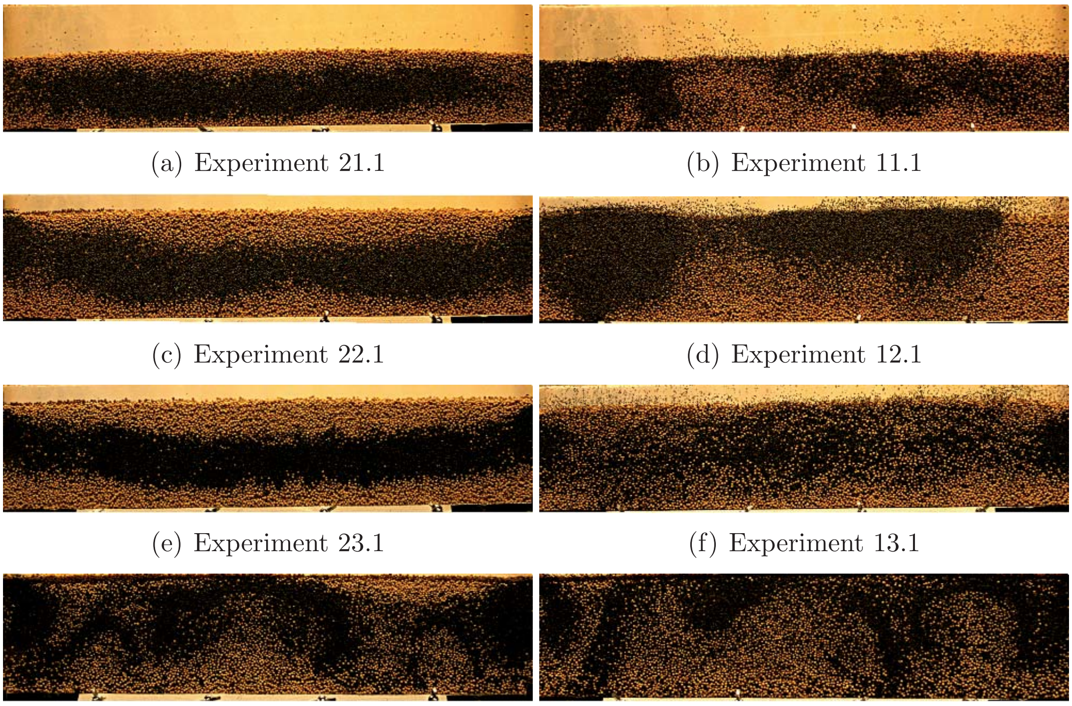
in size and shape does not dismiss the formation of convection rolls. This can be proved by using cheap sand from the drug store that is intentionally meant for decorative purposes. As it happens these experiments gave me the best results, concerning convection rolls (e.g. figure 6 and 15). Perhaps the undefined and irregular sizes and shapes have an influence on fluidization and avoid yokes.
Experiments with salt led to stuck material and completely unexpected results, this might come from the huge size difference in comparison mustard seeds. The various granulates also have different characteristics in terms of electrostatic behaviour. Poppy seeds and the deco-sand is very easy to charge up, during the filling process and also within the container. Meanwhile the salt had no such capacities which might be another reason for the extraordinary outcome. Furthermore, the salt grains grinded the container walls a bit and led a small amount of dust behind.
In general, every material that is large enough, so Van-der-Waals forces have no influence can be used[58].
An interesting question is, whether the convection mechanism originates from the segregation or the other way around. To solve this issue experiments with mono disperse granulate were performed by Frank Rietz[59]. He proved that convection can still occur although "much less effectively."[60]

Figure 21: The machine made by Prashant Vipul to sieve out the granulate[62].

[58]Cp. Convection and Segregation, 6.
[59]Cp. *ipid.*, 53.
[60]*Ipid.*
[62]Adapted from: Prashant, Vipul (2011): Pattern Formation in Granular Materials, private communication.

6 Result comparison

6.1 Air humidity



(a) Experiment 21.1

(b) Experiment 11.1

(c) Experiment 22.1

(d) Experiment 12.1

(e) Experiment 23.1

(f) Experiment 13.1

(g) Experiment 24.1

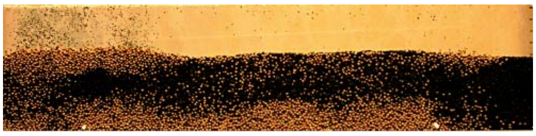
(h) Experiment 14.1

Figure 22: The experiments on the left just distinguish from the ones on the right through the humidity. Each picture was taken after ca. 6000 rot. During the runs on the left an air de-humidifier was used to lower the value to under 50% (exact value can be seen in the appendix). The humidity on the right was around 70%. It is visible that the results on the left show mostly radial segregation, meanwhile on the right the usual, sometimes unstable, pattern formation occurred. Furthermore, the material seems to stick less to the walls, this might enable one to draw the conclusion that a higher humidity is desirable for the experiments. This accords with Frank Rietz's observations[64], yet it is not clear why radial segregation occurs when the humidity and the fill level are lower. This phenomenon might be explained with the assumption that the electro static forces are lower or the material itself less sticky, thus the whole material better fluidized, so the of double brazil nut effect which perhaps drives the radial segregation is more likely to occur. This observation, however, cannot be made in general, since it did not appear in experiment 24.1 (figure 22 g) in which the fill level was slightly higher. Despite these new results, it has to be pointed out that convection can absolutely occur, although the humidity is lower, as shown in figure 22 g and h.

[63] Cp. Convection and segregation, 95.

6.2 Reproduceability rate

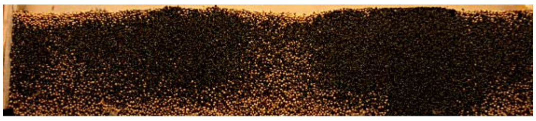
(a) Experiment 8.1



(b) Experiment 10.1

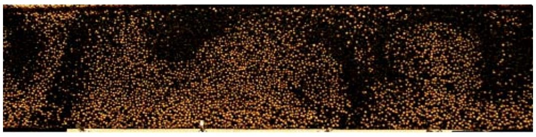
(c) Experiment 8.2

(d) Experiment 10.2

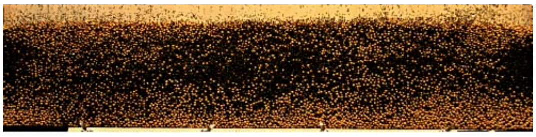


(e) Experiment 8.3

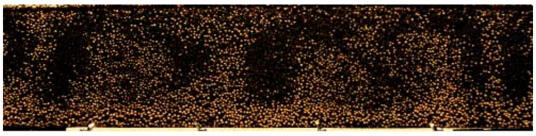
(f) Experiment 10.3



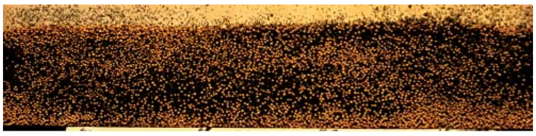
(g) Experiment 14.1



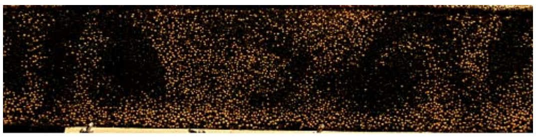
(h) Experiment 13.1



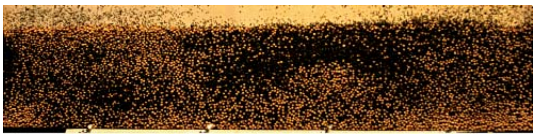
(i) Experiment 14.2



(j) Experiment 13.2



(k) Experiment 14.3

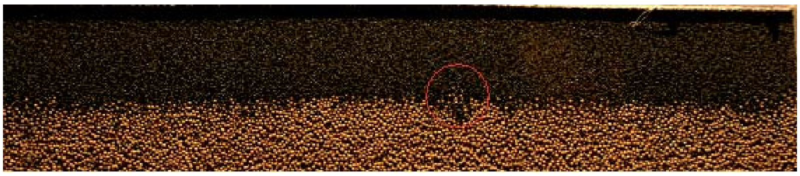


(l) Experiment 13.3

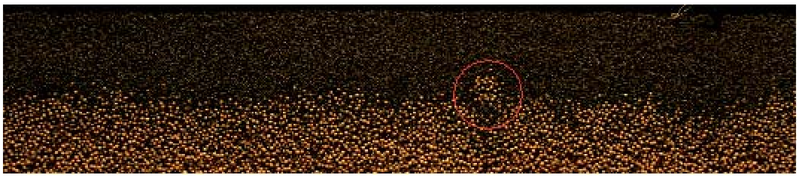
Figure 23: The pictures were taken after ca. 6000 rot. there are always three different runs with the same settings. The reproducibility rate was in general very high, concerning the pattern formation and mechanisms that occurred. As a rule of thumb, a reproduction of the results is more likely the less movement there is, because the risk of disturbing factors is smaller and they will not have a huge impact when the movement of the whole material is limited. This proves that the different parameters will influence the outcome and should allow anyone to reproduce the pattern. Yet, completely different results are interesting as well and require further investigations which will often lead to new insights.

7 Further observations

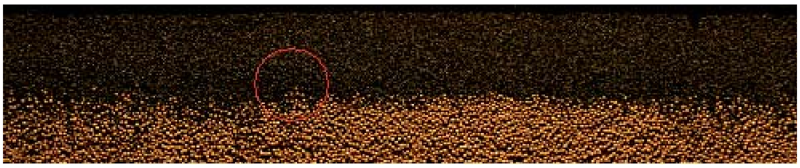
7.1 Cluster of particles



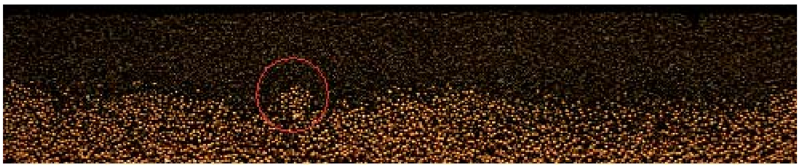
(a) Experiment 4.1, 20 rot.



(b) Experiment 4.1, 100 rot.

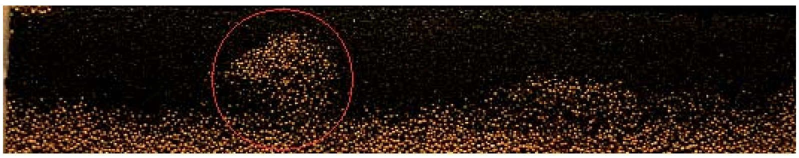


(c) Experiment 6.3, 20 rot.



(d) Experiment 6.3, 100 rot.

(e) Experiment 9.1, 20 rot.

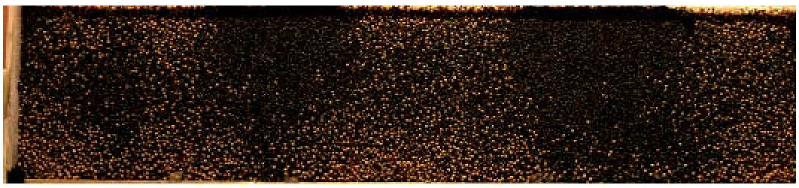


(f) Experiment 9.1, 100 rot.

Figure 24: At the beginning of some experiments a cluster of particles moved to the top, in the opposite direction of the normal granular movement. This observation is completely unexplained, as well as its origin. As a matter of fact, it occurred in diverse experiments with different settings, so no key element to its development can be figured out. This phenomenon does not seem to influence the later pattern formation, though. In most of the cases, the cluster only consist of several beads, but as shown in figure 23 f, also larger accumulations are possible. Furthermore, this phenomenon can often be made out very soon but no fixed rules could be set up. Further experiments which examine the relation of different granulate and these clusters should be done, although it is unclear how to trigger them actively, yet.

7.2 Cone-shaped stripes

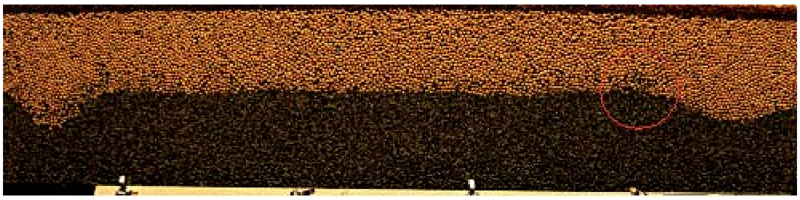
(a) Experiment 4.3, 2000 rot.



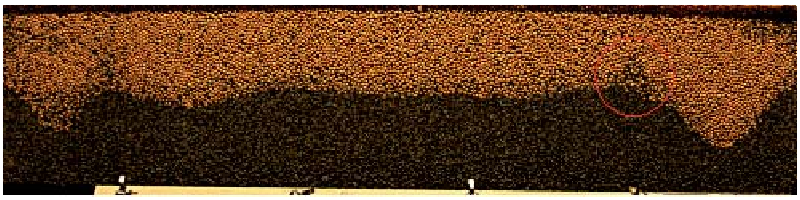
(b) Experiment 6.1, 2600 rot.

Figure 25: In a lot of cases in which axial segregation took place, the stripes were not perfectly straight and parallel but instead more like cone-shaped with the larger part pointing to the bottom. The reasons for that have to be speculated, but the assumptions that this occurings can be seen as the phase slightly before, or during the transition to convection rolls, seems to be plausible. In order to do further research, the critical fill level, Cc, is of high importance.

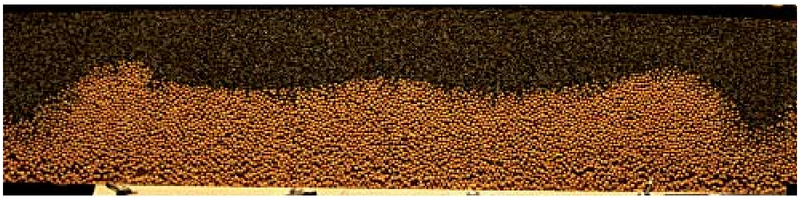
7.3 3d spots



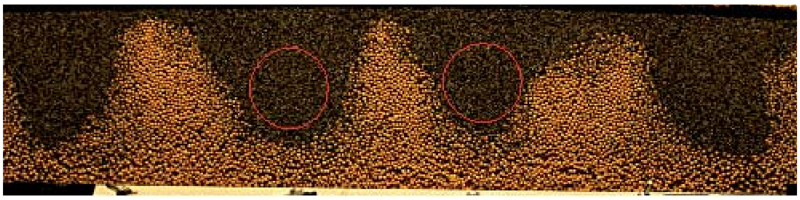
(a) Experiment 15.1, 1000 rot.



(b) Experiment 15.1, 2000 rot.



(c) Experiment 15.2, 1000 rot.

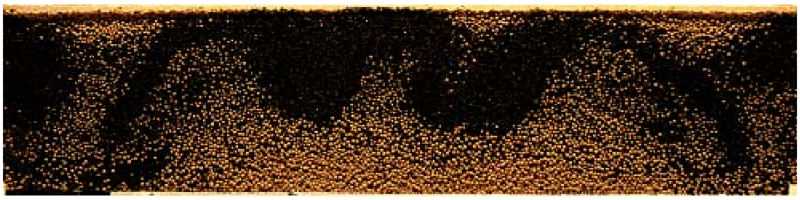


(d) Experiment 15.2, 1000 rot.

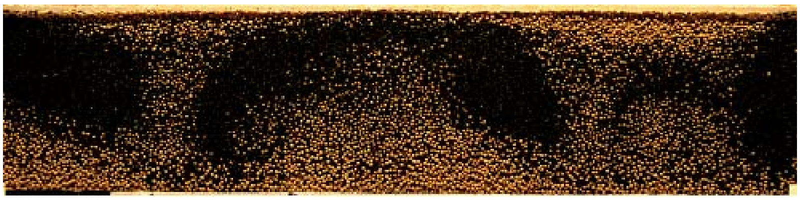
Figure 26: Some experiments showed an unexplainable and until now undescribed phenomenon. Sometimes and, as it seems, randomly a round spot opened in the granulate structure which enabled the particles to move along the third dimension which means back and forth, in the middle of the container. This movement is normally seen in the two horizontal fluidized zones and to a certain level also in other parts, for example the middle. But a spot that allowed the granulate to move largely in the third dimension and that enables the beads to change the layers has never been recorded or described before. Thus its formation and origin is completely unexplained. However, these spots occurred in experiment 15.2 (figure 25 c, d) directly inside of a convection roll, thus it can be assumed that they are created by the higher density there. This can only be seen in the videos but not in the pictures.

7.4 Starting condition

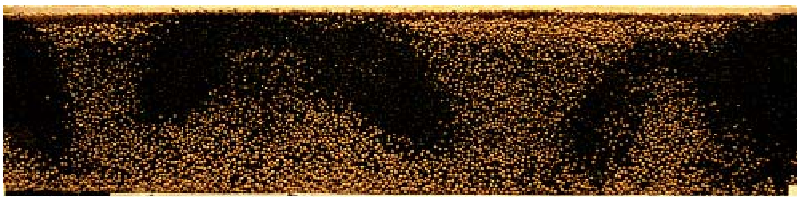
(a) Experiment 26.1, Starting condition.



(b) Experiment 26.1, 1000 rot.



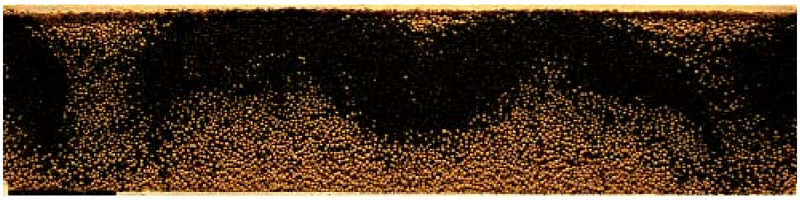
(c) Experiment 26.1, 2000 rot.



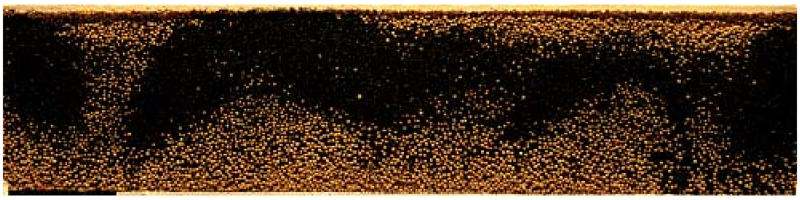
(d) Experiment 26.1, 9000 rot.

Figure 27: In order to test the influence of the starting condition, an extreme example for an unequal filled cell was created (figure 27, 28, 29). Surprisingly this did not make a huge difference. However, since the movement on the left side was much larger, the convection could develop faster. The roll on the left side right after the beginning is an indicator for the benefits of a more free movement to convection. There furthermore seems to be more motion in general, since the pattern was not stable at all, but did change between different convection structures.

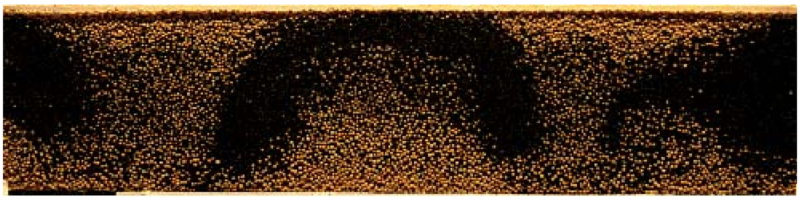
(a) Experiment 27.1, Starting condition.



(b) Experiment 27.1, 1000 rot.



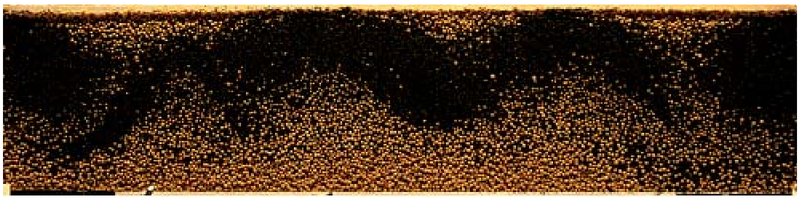
(c) Experiment 27.1, 2000 rot.



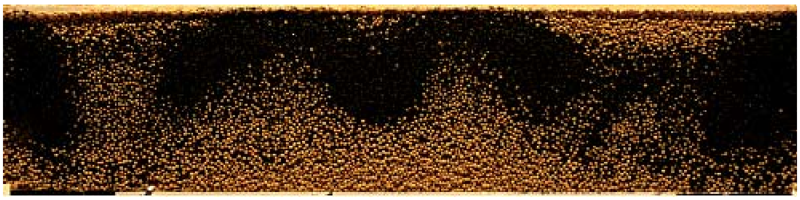
(d) Experiment 27.1, 9000 rot.

Figure 28: This figure shows the opposite of figure 28. The container was rotated along its horizontal axis and, as assumed, convection started were the free space was.

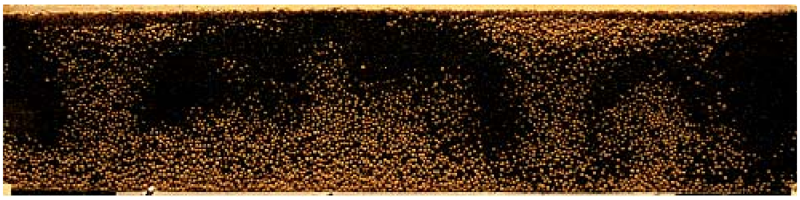
(a) Experiment 25.1, Starting condition.



(b) Experiment 25.1, 1000 rot.



(c) Experiment 25.1, 2000 rot.



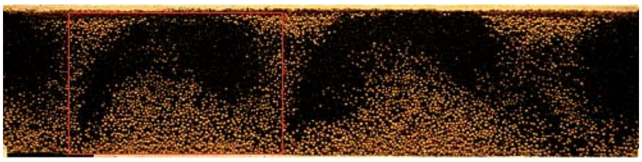
(d) Experiment 25.1, 9000 rot.

Figure 29: This experiment should prove the influence of an unequal filling. Often there forms a pile during the filling procedure which was exaggerated in this run. The outcome was no surprise: the convection rolls started at the lateral edges, where the particles could move most freely. When comparing experiment 26.1 (figure 26), 27.1 (figure 27) and 25.1 (figure 28), the outcome was not influenced a lot by the different starting conditions. However, convection always started where there was the most space available.

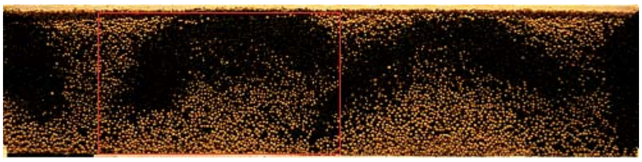
7.5 Traveling rolls

Another yet unexplained appearing are travelling rolls and stripes. Although the cell is completely even, it seems like the one lateral wall is producing new waves, while the other end swallows them. It is unclear how this motion can be influenced or why the granulate behaves like this[64]. However, it seems to be plausible that a motion of the whole granulate in the middle hat to be compensated somehow, thus it would be necessary to observe the differences in the horizontal zones. Maybe there is a stream within the middle of the box to one end, driven by convection and a contrary flow along the horizontal boundary. But these considerations are until now just speculations. Against this theory counts the issue that also travelling stripes were observed.

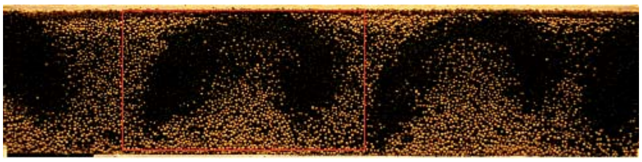
[64]Cp. Convection and segregation, 63.



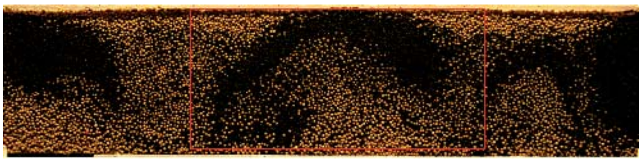
(a) Experiment 27.1, 4000 rot.



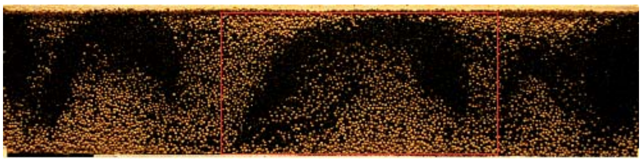
(b) Experiment 27.1, 4500 rot.



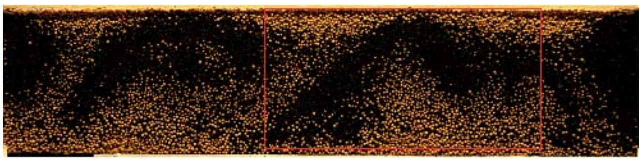
(c) Experiment 27.1, 5000 rot.



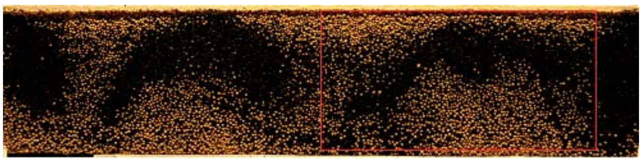
(d) Experiment 27.1, 5500 rot.



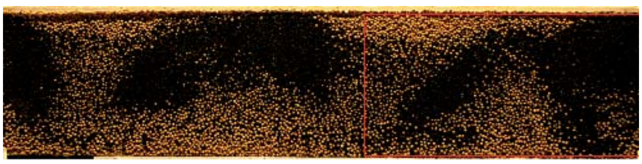
(e) Experiment 27.1, 6000 rot.



(f) Experiment 27.1, 6500 rot.



(g) Experiment 27.1, 7000 rot.



(h) Experiment 27.1, 7500 rot.

Figure 30: A travelling roll was marked by a red rectangle. The speed differs but is approximately the half wavelength during 500 rotations. Furthermore, it can be seen that not only one single roll is moving to the edge but other ones are created and follow them.

8 Conclusion

One of the most important issues that should be treated when someone would like to continue this work, is, how to define what a convection roll actually is. If it was possible to recognize a roll perfectly, it would be of no great effort to show the results in a plotted graph and point out the relations of parameters and results. The best solution for this would be to write a video analysis program that compares certain circle-like structures with the patterns, since it is hardly possible to track the movement of every single particle (especially, because of the 3d movement) and if only a few tracers are used, it is not possible to draw solutions for the whole cell. Furthermore, one should keep in mind that the movements within the box are very complex and so is the outcome which means the results could be presented with graphs and numbers but to see the relations the recordings of the experiments should, under no circumstances, be neglected. Unfortunately, without such a program, the analysis of the records remain completely subjective. On the other hand it would be of course possible to simulate these experiments, in order to eliminate all disturbing factors. However, so far no simulations for 3d experiments have been performed. Referring to the definition of a convection roll, it can be said that it is easiest to make out either a single roll or a complete convection structure, but it is hardly possible to divide the whole structure into single roll, since transition and influence between the rolls are always present.

While considering the initial doubts about the practicability of examinations and experiments of convection rolls, I can proudly say that I managed to gain convection rolls, stripes and other interesting patterns which might be the basis for further studies in the future. I furthermore hope, to have given a short summary of the diverse mechanisms and issues within the box and to have given an insight in the theory behind their origin.

9 Appendix

Experiment	°C	Humidity in %	1. Mass in g	2. Mass in g	C	Rpm
3.3	/	/	pop 88.18	mus 84.65	0.8	13
3.4	.	.	.	.	.	.
3.5	.	.	.	.	.	.
4.1	/	/	pop 88.18	mus 84.65	0.8	20
4.2	.	.	.	.	.	.
4.3	.	.	.	.	.	.
5.1	/	/	pop 88.18	mus 84.65	0.8	47
5.2	.	.	.	.	.	.
5.3	.	.	.	.	.	.
6.1	/	/	pop 88.18	mus 84.65	0.8	25
6.2	.	.	.	.	.	.
6.3	.	.	.	.	.	.
7.1	/	/	pop 88.18	mus 84.65	0.8	15
7.2	.	.	.	.	.	.
8.1	/	/	pop 88.18	mus 84.65	0.8	20
8.2	.	.	.	.	.	.
8.3	.	.	.	.	.	.
9.1	/	/	mus 107	san 227	0.9	20
9.2	.	.	.	.	.	.
9.3	.	.	.	.	.	.
10.1	/	/	mus 52	san 120	0.4	20
10.2	.	.	.	.	.	.
10.3	.	.	.	.	.	.
11.1	21	75	pop 53.0	mus 56.0	0.5	20
11.2	22	69	.	.	.	.
11.3	22	70	.	.	.	.
12.1	21	75	pop 71.59	mus 86.81	0.7	20
12.2	22	69	.	.	.	.
12.3	22	70	.	.	.	.
13.1	22	73	san 167.78	mus 86.81	0.8	20
13.2	22	70	.	.	.	.
13.3	22	67	.	.	.	.
14.1	22	71	san 228.85	mus 110.44	0.9	20
14.2	22	68	.	.	.	.
14.3	20	68	.	.	.	.
15.1	21	63	pop 94.86	mus 111.30	0.9	20
15.2	21	63	.	.	.	.
15.3	20	63	.	.	.	.
16.1	21	62	sal 203.37	mus 109.73	0.7	20
16.2	21	62	.	.	.	.
16.3	20	64	.	.	.	.
17.1	20	65	pop 109	mus 32.3	0.7	20
18.1	22	52	.	.	.	20
19.1	23	49	.	.	.	.
20.1	24	47	pop 84	mus 88	0.7	20

Experiment	°C	Humidity in %	1. Mass in g	2. Mass in g	C	Rpm
21.1	23	46	pop 53.0	mus 56.0	0.5	20
22.1	24	46	pop 71.59	mus 86.81	0.7	20
23.1	24	44	san 167	mus 86.81	0.8	20
24.1	23	46	san 228.58	mus 110.44	0.9	20
25.1	20	60	san 227	mus 102.64	0.9	20
26.1	19	60	.	.	.	20
27.1	19	64	.	.	.	20
28.1	17	64	rp 128	san 127	0.7	20
28.2	19	60	.	.	.	.
28.3	19	59	.	.	.	.

Experiment	Comments and observations
3.3	3 stripes form after 1600 rotations. Later transition to slight convection rolls after ca. 5000 rot.
3.4	Same as above.
3.5	Same as above. Highly reproducible, very stable pattern formation.
4.1	Extraordinary movement to the top of particle cluster at the beginning. Fluidized zone on the right side visible. Also 3 stripes after ca. 1600 rot., but not as nicely shaped as before. Later again transition to convection rolls after ca. 5000 rot., better shaped than in experiment 3.
4.2	At the beginning the same as above, but not that well shaped and a bit more unstable. Later two rolls fuse to one, after 9700 rot.
4.3	2 stripes form after 1400 rot, cone shaped. Later transition so slight rolls after 8400 rot. Reproducibility rate not that high.
5.1	Very unstable due to extremely high rotation speed. Still axial segregation with stripes on the same places as before
5.2	Same as above.
5.3	Way more fluidized at the beginning. Granulate gets mixed thoroughly. 2 stripes form after ca. 10000 rot. Highly reproducible, but very unstable.
6.1	2 large segments of the smaller beads form after 1000 rot. Slight convection visible, cone shaped stripes. Segregation in the left fluidized zone after 5500 rot. Looks like 3 stripes, indicates the shift of the wavelength.
6.2	Same as above, but no clear segregation in the fluidized zones. Convection visible.
6.3	Cluster of particles moving to the top at the beginning, such as in 4.1. Pattern formation seems to be unstable, but 3 cone shaped stripes form after 2300 rot. Convection is present but no clear convection rolls.
7.1	3 nicely shaped stripes after 1000 rot, more stable than experiment 6. Pattern very similar to experiment 6.
7.2	Fluidized zone at the top clearly visible. Extraordinary pattern formation, very symmetrical. Mustard seeds stay at the bottom until 3000 rotations. Convection roll on the right side after 2500 rot, but not in usual sense. Convection and convection rolls present but not perfectly stable.
8.1	Mustard seeds move very fast to the top fluidized zone. Hills and valleys on the top fluidized zone visible, due to density differences. Big stripe of mustard seeds in the middle after 1000 rot. Large segments of beads and huge segregation.
8.2	Same as above.
8.3	Same as above. Very stable and high reproducibility rate.

Experiment	Comments and observations
9.1	Again, cluster of particles moving to the top. Very fast movement, probably because of the smaller granulate. Convection roll in the right fluidized zone, but not in the usual sense, after 800 rot. A lot of convection, although rolls are not clearly visible (but present). Box is slightly askew which explains the segregation on the right.
9.2	Same as above.
9.3	Same as above. High reproducibility rate, but pattern is rather unstable. After experiment 9 a new perfectly straight box was used.
10.1	Radial segregation but with peaks within the granular. Accumulation on the right side. a lot of electrostatic forces.
10.2	Similar to above, but not that nice shaped. Radial segregation is more uneven.
10. 3	Same as above.
11.1	In contrast to experiment 10, no radial segregation, but accumulations of granulate.
11.2	Transition of several accumulations, very unstable.
11.3	Same as above. large accumulation of smaller beads on the left side.
12.1	Radial segregation at the very beginning. Then accumulation of smaller beads on the left, such as in 12.3 After 1400 rot. very clear segregation.
12.2	Same as above, but with a slight shift to the right.
12.3	same as above, but different zones of granulate are more compact.
13.1	Radial segregation at the beginning, but mixed thoroughly after 6500 rot. Two accumulations of small beads at the lateral walls. There seems to be a kind of horizontal segregation after 10800 rot.
13.2	Granulate gets mixed way more faster than in 13.1. Horizontal segregation is visible again.
13.3	Same as above, but without horizontal segregation.
14.1	Typical spikes in the fluidized zones at the beginning. Later transition to convection rolls there but in reversed sense, influencing the whole filling. Very symmetrical pattern formation with nicely shaped convection rolls on both sides. Convection pulls through the whole container.
14.2	Same as above.
14.3	Horizontal fluidized zones visible at the beginning. Very Similar pattern, granulate is now interchanged. Convection rolls at the beginning are even better. All in all perfect rolls and nice pattern formation, although not always exactly the same.

Experiment	Comments and observation
15.1	Horizontal fluidized zones again visible. Pattern formation similar to experiment 14. Movement slower in comparison to 14, granulate seems to be less fluidized. Convection rolls occur, nevertheless, but not that symmetrical. There seems to be a spot at the right side with movement in the 3rd dimension.
15.2	Very interesting pattern after 3200 rot. Stripe like formation beginning at the sides which than influences the whole material, but also unstable. Horizontal fluidized zones seem to be much larger. Granulate disappears in the middle of the container in the 3rd dimension. Large segments of segregated beads.
15.3	No such pattern as above, but again large segments of segregated particles. Also another spot like opening for movement in the 3rd dimension. Very interesting observations but low reproducibility rate in experiment 15.
16.1	Spikes at the beginning, but granulate gets mixed thoroughly fast, due to small salt beads. Later axial segregation after 5100 rot. Two stripes merge into one after 10600 rot.
16.2	Completely different pattern formation because of roughening of the walls by the salt which leads to stuck material. This creates less space, thus accumulations of salt in those regions are generated.
16.3	Same as above. Extremely fast movement and mixing at the beginning.
17.1	Stuck material. No other interesting results. Stuck material can be avoided by using small fill level and poppy seeds to remove salt particles.
18.1	Very small movement due to high fill level. Convection roll in the right fluidized zone. Air dehumidifier was used.
19.1	Convection roll at the right directly from the beginning. Rest of the granulate is not uniform. Pattern formation is completely unexplainable, but similar to very early experiments with askew cell.
20.1	A kind of radial segregation but not uniform with segments of segregated beads.
21.1	Perfect radial segregation with electrostatic forces visible. See experiment 11.
22.1	Radial segregation, later one stripe of mustard seeds. See experiment 12.
23.1	Radial segregation with a slight curve. See experiment 13.
24.1	Convection starts at both lateral edges in usual sense and then influences the whole container. Both rolls later change sense. Double roll in the middle of the container. In contrast to the other experiments with lower humidity, the outcome did not differ from the normal results.
25.1	Convection starts at lateral edges, due to starting condition (Pile). Wave-like pattern after 600 rot.
26.1	Convection starts at left lateral wall, because of free space but surprisingly also at the other side, where density is much higher. Left roll detaches and moves to the middle after 800 rotations. A lot of movement, thus very unstable.

Experiment	Comments and observations
27.1	Convections starts in the middle due to starting conditions. There seems to be a shifting to the right.
28.1	Signs of convection rolls but not clearly distinguishable.
28.2	Same as above.
28.3	Same as above.

Symbols in table

pop	Poppy seeds
mus	Mustard seeds
san	Sand
sal	Salt
rp	Rice pudding grains
rot	Rotations

Concerning Table:
Since every run was mostly performed three times with the same settings, the dot means "same value as above".

Further comments:
The specifications of the container are always the same if nothing else is written.

During the recorded experiments two different cells were used, although the specifications and material etc. are the same, this might lead to small variations.

The dehumidifier was used in experiment 17.1 - 24.1 as can be seen on the humidity.

If nothing else is mentioned, the figures were made by myself, this is especially valid for the recordings of my experiments. Most sketches were also made by myself, but the idea is often taken from Frank Rietz's work, as stated.

The records of the experiments are treated with two filters in order to improve definition and colour.

List of Figures

9.1 Public outreach

Publications

- Adrian Ebert: Auf der Frühjahrstagung der DPG, Detektor (2015).

Poster

- Ann-Kathrin Raab, Adrian Ebert: A 2D computer simulation to analyse convection rolls in rotating 2D packings, Dresden, October 16- 19, 2014
- Ann-Kathrin Raab, Adrian Ebert: A Computer Simulation and Experiments to Explain the Phenomenon of Convection Rolls in Rotating Boxes, Berlin, March 15-20, 2015

Further activities

- Participation at international masterclass, Munich, March 23, 2015
- Organisation of masterclass at the Ignaz-Günther Gymnasium, July 21, 2015
- Stipend for a workshop at CERN, November 11-14, 2015

Movies

- Records of every experiment and comparisons
  Youtube: *https://www.youtube.com/channel/UCJugdtRL_c7jb8z3RR-Rnvg*

9.2 Bibliography

- Morsch Oliver: Sandburgen und Seifenblasen. Weinheim, Wiley-Vch, 2005.
- Buchaman Mark: Drum roll
  URL: http://www.nature.com/nphys/journal/v7/n10/full/nphys2115.html (2015)
- Rietz, Frank (2012): Convection and Segregation of beads in a flat rotating box.
- Prashant Vipul (2011): Pattern Formation in Granular Materials, privat communication